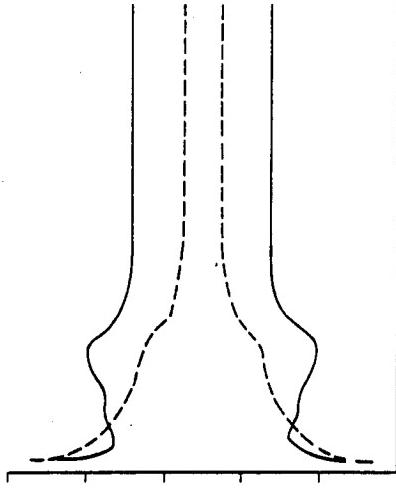


**OPTIMIZATION TECHNIQUES
APPLIED TO
PASSIVE MEASURES FOR IN-ORBIT
SPACECRAFT SURVIVABILITY**

HV410-12

**FINAL REPORT
(NAS8-37378)**



**Robert A. Mog
D. Marvin Price**

November 1987

**Prepared for George C. Marshall Space Flight Center,
Marshall Space Flight Center, AL 35812**

BM21-8/21

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"OPTIMIZATION TECHNIQUES APPLIED TO PASSIVE MEASURES FOR IN-ORBIT SPACECRAFT SURVIVABILITY" IS A SIX-MONTH STUDY, DESIGNED TO EVALUATE THE EFFECTIVENESS OF THE GEOMETRIC PROGRAMMING OPTIMIZATION TECHNIQUE IN DETERMINING THE OPTIMAL DESIGN OF A METEOROID AND SPACE DEBRIS PROTECTION SYSTEM FOR THE SPACE STATION CORE MODULE CONFIGURATION. THE EFFORT IS DIRECTED BY SHERMAN L. AVANS, ED52.

THE AUTHORS WISH TO THANK MR. AVANS FOR HIS OVERALL DIRECTION AND "REAL WORLD" INPUTS ON THIS STUDY. WE ALSO WANT TO THANK MS. JENNIFER HORN FOR PROVIDING DIRECTION ON THE DESIGN TRADES THAT WERE PERFORMED AS WELL AS MANY OF THE REFERENCES AND BASELINE PARAMETERS.

THE AUTHORS ALSO WISH TO THANK FRANCES CHEEK OF SAIC FOR HER CONSULTATIONS AND QUALITY REVIEW OF THIS REPORT.

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MOTIVATION

- MANY FUNCTIONAL IMPACT PREDICTORS/MODELS ARE AVAILABLE
- MODELS ARE SOMETIMES CONFLICTING/CONFUSING
- MODELS ARE OFTEN NOT WELL-DOCUMENTED
- MODELS HAVE DIFFERENT PARAMETER SPACES AND DIFFERENT ORIGINS/ASSUMPTIONS
- FUNCTIONAL PREDICTORS ARE SUPERIOR TO NON-ANALYTICAL MODELS FOR DESIGNER TRADE-OFF STUDIES

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HOW THIS STUDY COMPLEMENTS OTHER EFFORTS

- PROVIDES A TOOL FOR DISSECTING THE MASS OF IMPACT PREDICTORS/ MODELS AVAILABLE TO THE DESIGNER
- ESTABLISHES OPTIMAL DESIGN DATA BASED ON THE CURRENT PREDICTORS FOR COMPARISON WITH TESTING
- COMPLEMENTS BOEING'S EFFORTS WITH A HOST OF PERTINENT DESIGN TRADEOFFS
- ESTABLISHES A DATA BASE OF PREDICTOR ATTRIBUTES

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WHAT YOU WILL SEE

- A DISCUSSION OF OPTIMIZATION TECHNIQUES
- SIGNIFICANT DESIGN TRADES FOR SEVERAL PREDICTORS
UNDER DIFFERENT ASSUMPTIONS
- AN ASSESSMENT OF GEOMETRIC PROGRAMMING

WHAT YOU WON'T SEE

- THE DEVELOPMENT OF NEW PREDICTORS
- THE NOMINATION OF A PREDICTOR
- A RECOMMENDED CORE MODULE DESIGN
- CONSIDERATION OF MLI, SUPPORT STRUCTURE, OR OTHER
DESIGN ACCOUNTS (STRESS, THERMAL, ETC.)

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CONTENTS

- I. OPTIMIZATION TECHNIQUES BACKGROUND AND COMPARISON
- II. NYSMITH PREDICTOR APPLIED TO IDEALIZED SCENARIO
- III. NYSMITH PREDICTOR APPLIED TO CORE MODULE CONFIGURATION
- IV. GEOMETRIC PROGRAMMING APPLIED TO THE BOEING SUBPREDICTORS
- V. GEOMETRIC PROGRAMMING APPLIED TO THE BOEING PREDICTOR
- VI. GEOMETRIC PROGRAMMING APPLIED TO THE VELOCITY-INTEGRATED BOEING PREDICTOR
- VII. CONCLUSIONS
- VIII. RECOMMENDATIONS
- IX. REFERENCES
- X. APPENDICES
 - A. MATHEMATICS
 - B. COMPUTER CODES

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TERMINOLOGY

- WALL - THE CORE MODULE PRESSURE SURFACE OR STRUCTURE
- BUMPER - A SHIELD OR PLATE SPACED OUTBOARD FROM THE WALL
- OPTIMAL RATIO - THE THICKNESS DISTRIBUTION (IN PERCENT) BETWEEN THE BUMPER AND WALL THAT OPTIMIZES THE DESIGN OBJECTIVE
- "WEIGHT" - THE SUM OF THE BUMPER AND WALL THICKNESSES
- WEIGHT - THE THEORETICAL DRY CORE MODULE EARTH-MASS AS ATTRIBUTED TO THE BUMPER AND WALL THICKNESSES AND MODULE CONFIGURATION.
- MISSION RISK - ONE MINUS THE PROBABILITY OF NO PENETRATION
- INDEPENDENT VARIABLE(S) - THE PARAMETER(S) THAT ARE CONTROLLABLE IN SOME SENSE BY THE SYSTEM DESIGNER
- GLOBAL - A FORM OF OPTIMIZATION THAT RESULTS IN THE OVERALL OR COMPREHENSIVE BEST SOLUTION
- LOCAL - A FORM OF OPTIMIZATION THAT RESULTS IN THE BEST SOLUTION FOR SOME NEIGHBORHOOD OF THE INDEPENDENT VARIABLE

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TERMINOLOGY (CONTINUED)

- | | |
|-----------------------------|--|
| FUNCTIONAL | - A MATHEMATICAL RELATIONSHIP THAT MAY BE WRITTEN EXPLICITLY |
| PREDICTOR | - A MODEL, EITHER FUNCTIONAL OR NON-ANALYTICAL, WHICH DESCRIBES THE IMPACT PHYSICS (E.G., NYSMITH, WILKINSON, BURCH, MODIFIED BURCH, PEN4, BOEING, MADDEN, RICHARDSON) |
| NONLINEAR | - A PREDICTOR WHOSE INDEPENDENT VARIABLES HAVE EXPONENTS THAT ARE NOT ALL EQUAL TO UNITY |
| DEGREE-OF-DIFFICULTY | - IN AN OPTIMIZATION TECHNIQUE, THE NUMBER OF VARIABLES THAT MUST BE SOLVED FOR MINUS THE NUMBER OF INDEPENDENT EQUATIONS AVAILABLE |
| CONSTRAINT | - AN EQUATION OR INEQUALITY WHICH LIMITS THE USAGE OF A PREDICTOR |
| POSYNOMIAL | - A POLYNOMIAL WITH POSITIVE COEFFICIENTS AND WHOSE INDEPENDENT VARIABLES ARE POSITIVE-VALUED |

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TERMINOLOGY (CONTINUED)

- | | |
|-----------------------------|--|
| PARAMETER SPACE | - THE TOTAL NUMBER OF POSSIBLE INDEPENDENT VARIABLES ASSOCIATED WITH A PREDICTOR |
| IDEALIZED SCENARIO | - AN IMPACT SCENARIO SIMILAR TO A TEST SETUP AND CHARACTERIZED BY FLAT PLATES MODELLING THE BUMPER AND WALL AND NO SUPPORT STRUCTURE |
| OBJECTIVE FUNCTION | - THE EQUATION OR FUNCTION WHICH CHARACTERIZES THE OPTIMIZATION GOAL OF THE SYSTEM DESIGNER |
| INFLECTION | - A POINT IN A DESIGN TRADEOFF CURVE AT WHICH THE SLOPE CHANGES FROM DECREASING TO INCREASING, OR VICE VERSA |
| PIECEWISE CONTINUOUS | - A SET OF EQUATIONS, EACH OF WHICH IS CONTINUOUS, BUT WHEN COMBINED, MAY BE DISCONTINUOUS AT A FINITE NUMBER OF POINTS (E.G., WILKINSON, BOEING PREDICTORS) |
| MONOTONIC | - STRICTLY INCREASING, DECREASING, OR CONSTANT |

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SECTION I

OPTIMIZATION TECHNIQUES BACKGROUND AND COMPARISON

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WHAT YOU WILL SEE IN SECTION I

- PROTECTIVE SYSTEMS DESIGN OPTIMIZATION PROBLEM FORMULATION
- DISCUSSION OF SPECIFIC OPTIMIZATION TECHNIQUE ATTRIBUTES
- EXAMPLE APPLICATION

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WHAT OPTIMIZATION MEANS IN THIS STUDY

FINDING THOSE DESIGN THICKNESSES WHICH PROVIDE THE GREATEST PROTECTIVE CAPABILITY (WITH RESPECT TO THE METEOROID AND SPACE DEBRIS ENVIRONS) WHILE INDUCING THE LEAST WEIGHT, AND THUS COST.

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WHY THIS DESIGN OPTIMIZATION IS IMPORTANT

- METEOROID AND SPACE DEBRIS ENVIRONS
OFTEN DRIVE STRUCTURAL DESIGN
- SAFETY IS A HIGH PRIORITY
- DESIGN FEASIBILITY IS AT STAKE
- THE ENVIRONMENT IS NOT STATIC
- POLICY IS SIGNIFICANTLY AFFECTED BY COST
- IMPACT SCIENCE IS YOUNG

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PARAMETERS AND THE TASK OF THE SYSTEM DESIGNER

THE BASIC PARAMETERS ASSOCIATED WITH DESIGN OF THE PROTECTIVE SYSTEMS FOR SPACECRAFT WHICH MUST ENDURE THE THREAT OF METEOROIDS AND SPACE DEBRIS MAY BE CATEGORIZED AS MISSION PARAMETERS AND DESIGN PARAMETERS. TYPICALLY, MISSION PARAMETERS SUCH AS ORBIT, ACCEPTABLE MISSION RISK, MISSION DURATION, AND SPACECRAFT SIZE ARE USED TO DETERMINE THE DESIGN PROJECTILE MASS AND DIAMETER. THE PROJECTILE VELOCITY IS THEN CONSIDERED TO COMPLETE THE SET OF THREAT CHARACTERISTICS. DESIGN PARAMETERS SUCH AS BUMPER/WALL THICKNESS, DENSITIES, AREAS, AND SEPARATION ARE USED TO ASSESS THE EFFECTIVENESS OF THE DESIGN IN RESISTING PROJECTILE PENETRATION.

THE SYSTEM DESIGNER'S ROLE IS TO CREATE OR CHOOSE A RELATIONSHIP BETWEEN THE REQUIRED DESIGN PARAMETERS AND THE MISSION AND THREAT PARAMETERS. THE DESIGNER MUST THEN OPTIMIZE AN OBJECTIVE FUNCTION COMPOSED OF THE DESIGN PARAMETERS, E.G., WEIGHT.

PARAMETERS AND THE TASK OF THE SYSTEM DESIGNER

- **PARAMETERS**
 - MISSION (**THREAT**): PROJECTILE CHARACTERISTICS — DETERMINED FROM ORBIT (DEFINES ENVIRONMENT), ACCEPTABLE LEVEL OF RISK FOR MISSION, MISSION DURATION, SPACECRAFT SIZE
 - DESIGN: CONFIGURATION-SPECIFIC PARAMETERS OF PROTECTIVE SYSTEMS (e.g., thicknesses, densities, dimensions)
- **THE SYSTEM DESIGNER's ROLE**
 - DETERMINE THE DESIGN PARAMETERS BASED ON THE MISSION PARAMETERS
 - OPTIMIZE A SPECIFIC FUNCTION OF THESE DESIGN PARAMETERS

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CLASSICAL APPROACHES

IMPACT PREDICTORS MAY BE CLASSIFIED AS FUNCTIONAL OR NON-ANALYTICAL. AMONG FUNCTIONAL PREDICTORS, ONE HAS THEORETICAL (E.G., MADDEN EQUATION) AND EXPERIMENTAL (E.G., NYSMITH EQUATION) MODELS. NON-ANALYTICAL MODELS SUCH AS THE HULL CODE TYPICALLY ARE NUMERICAL TECHNIQUES EMPLOYING PARTIAL DIFFERENTIAL EQUATIONS TO SOLVE THE EQUATIONS OF SOLID AND FLUID MECHANICS.

THE FIRST STEP IN THE OPTIMIZATION PROCESS IS TO DEVELOP THE OBJECTIVE FUNCTION(S) IN TERMS OF FUNCTIONAL PREDICTOR(S). TYPICAL FUNCTIONS DESCRIBE LAUNCH WEIGHT OR COST ASSOCIATED WITH PROTECTIVE SYSTEMS.

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CLASSICAL APPROACHES

- PREDICTORS RELATE MISSION TO DESIGN PARAMETERS
 - FUNCTIONAL: THEORETICAL VS EXPERIMENTAL (e.g., Nysmith Equation)
 - NON-ANALYTICAL (e.g., HULL Code)
- OPTIMIZATION FUNCTIONS COMPOSED OF FUNCTIONAL PREDICTORS
 - FUNCTIONS DESCRIBING LAUNCH WEIGHT ASSOCIATED WITH PROTECTIVE SYSTEMS
 - FUNCTIONS DESCRIBING COST ESTIMATING RELATIONSHIPS ASSOCIATED WITH PROTECTIVE SYSTEMS

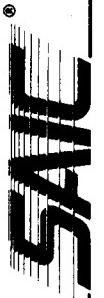


IDEALIZED SPACECRAFT IMPACT SCENARIO

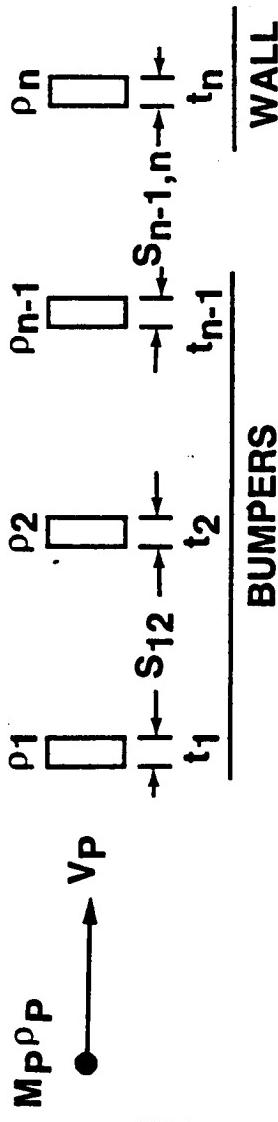
FOR ANALYSIS PURPOSES, AN IDEALIZED SCENARIO WAS DEVELOPED AS A BASIS TO COMPARE VARIOUS PREDICTORS.

THIS IDEALIZED SCENARIO IS SHOWN FOR A FAIRLY COMPLETE SET OF DESIGN AND PROJECTILE CHARACTERISTICS. THE "WEIGHT" FUNCTION ASSUMED IS THE PRODUCT OF THE PLATE DENSITY AND PLATE THICKNESS SUMMED OVER THE TOTAL NUMBER OF PLATES. AS WE SHALL SEE, FOR THE NYSMITH PREDICTOR, THERE IS ONLY ONE BUMPER AND ONE WALL. FURTHERMORE, THE NYSMITH PREDICTOR SHOWS NO DEPENDENCE ON BUMPER/WALL DENSITIES. THEREFORE, THE BUMPER THICKNESS IS THE INDEPENDENT VARIABLE, AND THE "WEIGHT" FUNCTION IS SUFFICIENTLY EXPRESSED AS THE SUM OF THE BUMPER AND WALL THICKNESSES.

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IDEALIZED SPACECRAFT IMPACT SCENARIO



- M_P = mass of projectile
- ρ_P = density of projectile
- v_P = velocity of projectile
- t_i = bumper thickness, $i = 1, 2, \dots, n-1$,
- t_n = wall thickness,
- ρ_i = bumper density, $i = 1, 2, \dots, n-1$,
- ρ_n = wall density
- S_{i+1} = distance between bumper i and bumper $i+1$.

“WEIGHT” FUNCTION:

$$W_T = \sum_{i=1}^n \rho_i t_i \quad \text{for constant normal plate areas.}$$

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ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

THE TRADITIONAL APPROACH TO CONTINUOUS AND OFTEN NONLINEAR FUNCTIONAL OPTIMIZATION HAS BEEN TO APPLY EXTREMA THEOREMS FROM THE CALCULUS. HOWEVER, THIS APPROACH ONLY PROVIDES SUFFICIENT CONDITIONS FOR LOCAL EXTREMA. THUS, THIS TECHNIQUE MAY FAIL IN TWO ENTIRELY DIFFERENT WAYS. IT MAY FAIL TO LOCATE CERTAIN EXTREMA, AND IF IT DOES LOCATE AN EXTREMA POINT FOR THE PROBLEM, THERE IS NO GUARANTEE THAT IT IS A GLOBAL EXTREMA. FURTHERMORE, THIS METHOD REQUIRES THE EVALUATION OF PARTIAL DERIVATIVES AND HAS NO PROVISIONS FOR INEQUALITY CONSTRAINTS INCLUDED IN THE PROBLEM FORMULATION. FINALLY, THIS METHOD IS CUMBERSOME FOR PROTECTIVE SYSTEMS WITH A LARGE NUMBER OF BUMPERS, SINCE THE NUMBER OF DETERMINANTS AND THE ORDER OF THE HIGHEST ORDERED DETERMINANT IS PRECISELY EQUAL TO THE NUMBER OF BUMPERS.

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ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

TRADITIONAL APPROACH

- THE EXTREMA THEOREM (ET) METHOD
 - APPLIES TO FUNCTIONAL PREDICTORS ONLY
 - PROVIDES SUFFICIENT CONDITIONS FOR LOCAL EXTREMA
 - NUMBER OF DETERMINANTS TO BE COMPUTED IS EQUAL TO THE NUMBER OF BUMPERS
 - ORDER OF HIGHEST ORDERED DETERMINANT IS EQUAL TO THE NUMBER OF BUMPERS
 - REQUIRES EVALUATION OF PARTIAL DERIVATIVES
 - HAS NO PROVISIONS FOR INEQUALITY CONSTRAINTS

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ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES (CONTINUED)

CONTRARY TO THE TRADITIONAL EXTREMA THEOREM APPROACH, THE GEOMETRIC PROGRAMMING TECHNIQUE PROVIDES THE GLOBAL OPTIMIZATION OF THE PROBLEM, PROVIDED IT IS FORMULATED IN POSYNOMIAL FORM. A POSYNOMIAL IS A POLYNOMIAL WITH POSITIVE COEFFICIENTS AND POSITIVE VALUES OF THE INDEPENDENT VARIABLES. A QUICK REVIEW OF THE VARIABLES SHOWN UNDER THE IDEALIZED SPACECRAFT IMPACT SCENARIO SHOWS THAT THE VARIABLES ASSOCIATED WITH THIS PROBLEM ARE INHERENTLY POSITIVE-VALUED. THUS, THE ONLY REQUIREMENT FOR GLOBAL OPTIMIZATION OF THESE TYPES OF PROBLEMS IS THAT THE IMPACT PREDICTOR BE A POLYNOMIAL WITH POSITIVE COEFFICIENTS. ANOTHER ADVANTAGE TO GEOMETRIC PROGRAMMING IS THE METHOD'S ABILITY TO ACCOMMODATE MANY TYPES OF INEQUALITY CONSTRAINTS.

ATTRIBUTES OF TWO OPTIMIZATION TECHNIQUES

(Continued)

ALTERNATIVE APPROACH

- THE GEOMETRIC PROGRAMMING (GP) METHOD
 - EMPLOYS THE ARITHMETIC-GEOMETRIC INEQUALITY
 - APPLIES TO POSYNOMIALS (POSITIVE-VALUED POLYNOMIALS)
ONLY
 - RESULTS IN GLOBAL OPTIMIZATION OF THE POSYNOMIAL
 - ACCOMMODATES MOST INEQUALITY CONSTRAINTS

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APPLICATIONS OF OPTIMIZATION METHODOLOGY

THE NYSMITH EQUATION WITH VARIABLE DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THERE IS NO DEPENDENCE ON BUMPER, WALL, OR PROJECTILE DENSITIES. THUS, WE SAY THAT THE NYSMITH PREDICTOR FORMS AN INCOMPLETE SET OF PARAMETERS. THE NYSMITH PREDICTOR IS ANALYZED BY BOTH OPTIMIZATION TECHNIQUES FOR THE ZERO DEGREE-OF-DIFFICULTY CASE WITH CONSISTENT RESULTS. IT IS ANALYZED USING GEOMETRIC PROGRAMMING ONLY FOR THE TWO DEGREE-OF-DIFFICULTY CASE, SINCE THE EXTREMA THEOREM METHOD DOES NOT HANDLE INEQUALITY CONSTRAINTS.

APPLICATIONS OF OPTIMIZATION METHODOLOGY

- THE NYSMITH EQUATION

$$\frac{t_2}{d} = \frac{5.08 V \cdot 278}{\left(\frac{t_1}{d}\right) \cdot 528 \left(\frac{h}{d}\right)^{1.39}}, \text{ valid for}$$

$$\frac{t_1}{d} \leq 0.5 \text{ and } \frac{t_2}{d} \leq 1.0,$$

where

V = projectile velocity,

d = projectile diameter,

t_1 = bumper thickness,

t_2 = wall thickness,

h = bumper wall separation

- INCOMPLETE SET OF PARAMETERS

- ANALYZED BY BOTH METHODS FOR ZERO DEGREE OF DIFFICULTY CASE (METHODOLOGY CONSISTENT) AND BY GP METHOD FOR 2 DEGREE OF DIFFICULTY CASE.

GP METHOD SEPARATES SOLUTION REGIONS AND UNCOVERS UNEXPECTED ANOMALIES

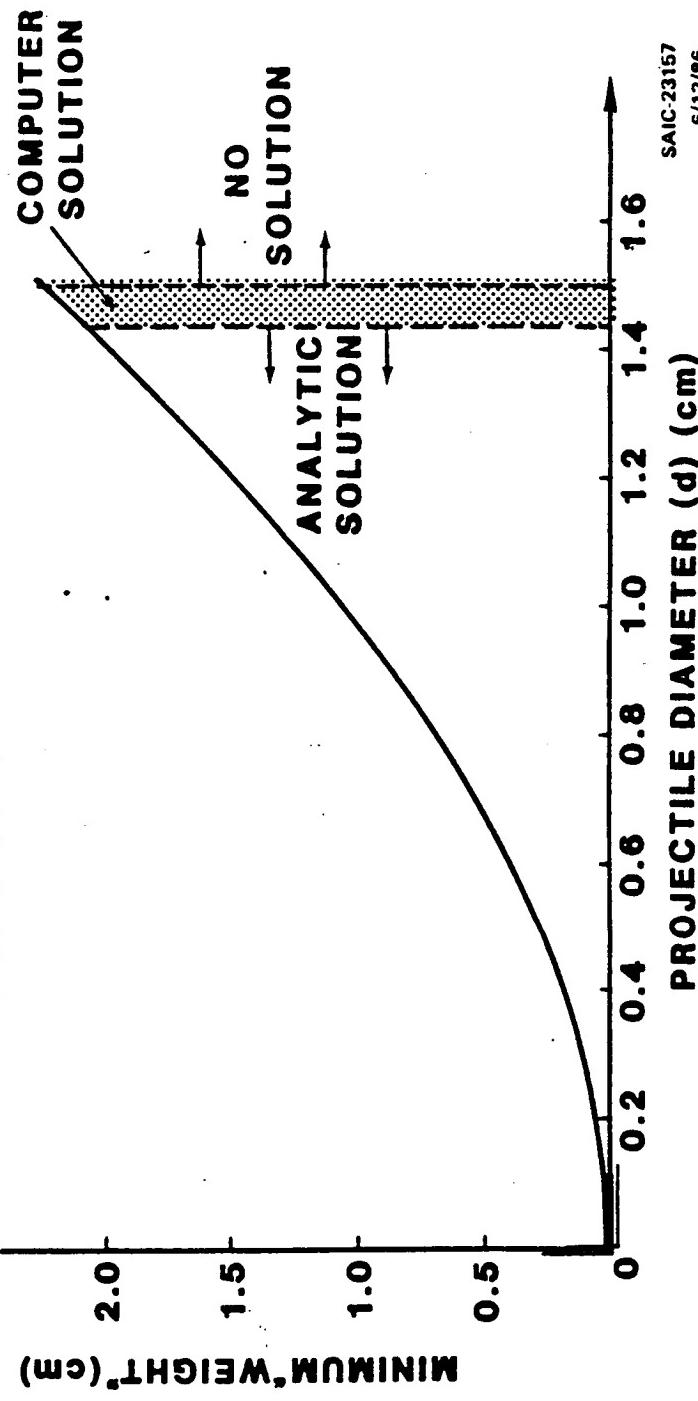
THE DEPENDENCE OF OPTIMAL DESIGN ON PROJECTILE DIAMETER IS SHOWN FOR A HYPOTHETICAL SCENARIO. IT TURNS OUT THAT THERE ARE THREE SOLUTION REGIONS ASSOCIATED WITH THE NYSMITH PREDICTOR. IN THE ANALYTIC SOLUTION REGION, IT IS DISCOVERED THAT THE MINIMUM "WEIGHT" MAY BE WRITTEN ANALYTICALLY IN TERMS OF THE SOLUTION PARAMETERS. IN THE COMPUTER SOLUTION REGION, THE GEOMETRIC PROGRAMMING DUAL VARIABLES MUST BE ITERATED TO OBTAIN THE OPTIMAL SOLUTION. FINALLY, IT IS FOUND THAT THERE EXISTS A REGION OF NO SOLUTION WHICH CORRESPONDS WITH A THIRD, PREVIOUSLY UNDISCOVERED, INEQUALITY CONSTRAINT TO THE NYSMITH PREDICTOR. THIS INEQUALITY CONSTRAINT IS INDEPENDENT OF THE ORIGINAL TWO CONSTRAINTS AND RESTRICTS THE APPLICABILITY OF THE NYSMITH PREDICTOR.

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**GP METHOD SEPARATES SOLUTION REGIONS AND
UNCOVERS UNEXPECTED ANOMALIES**

$h = 10 \text{ cm}$
 $v = 10 \text{ km/sec}$



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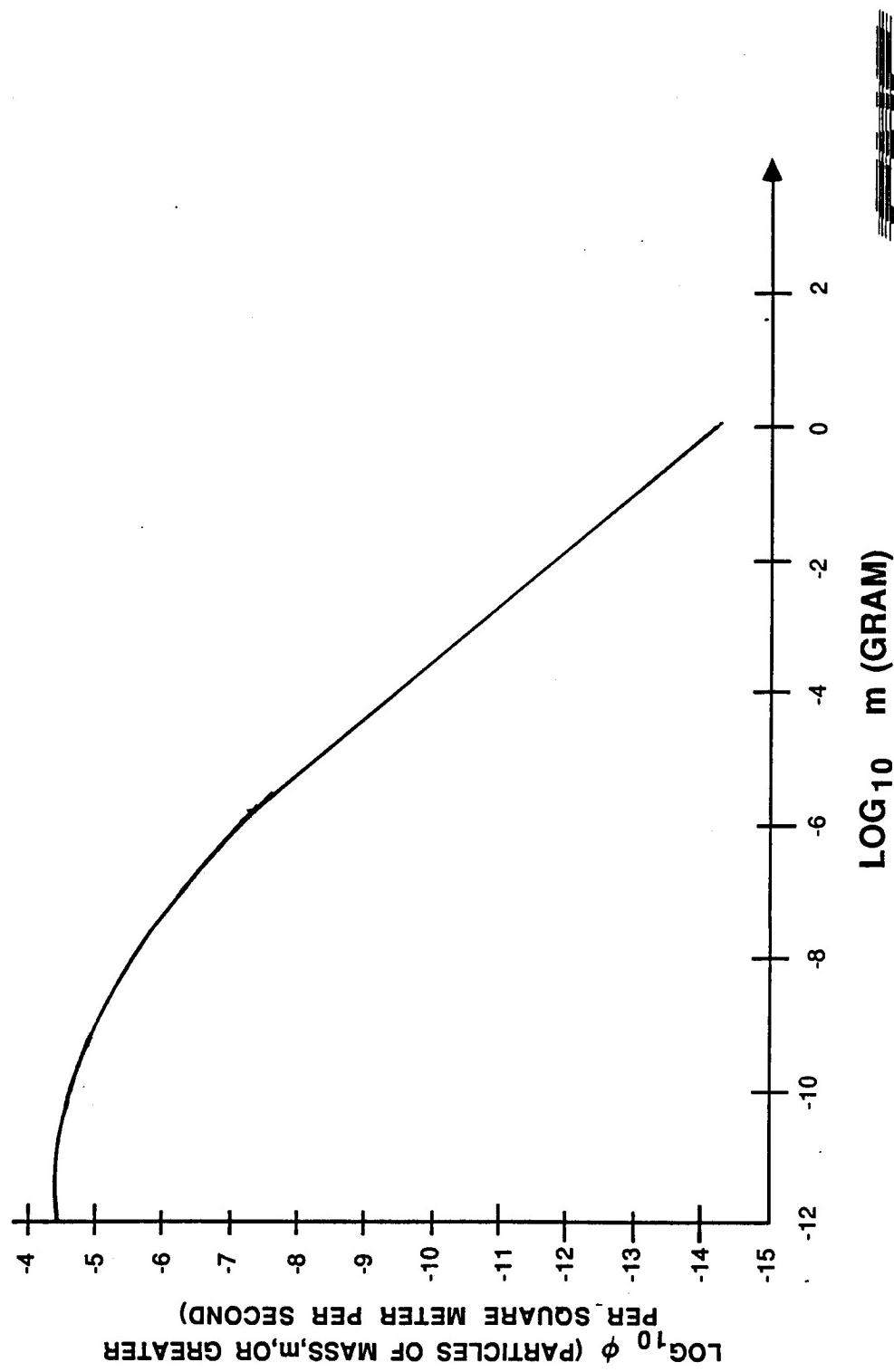
AVERAGE CUMULATIVE TOTAL METEOROID
FLUX-MASS MODEL FOR 1 A.U.

THE RELATIONSHIP BETWEEN METEOROID FLUX AND MASS WAS EXTRACTED
FROM NASA TM-86466, "A REVIEW OF MICROMETEOROID FLUX MEASURE-
MENTS AND MODELS FOR LOW ORBITAL ALTITUDES OF THE SPACE STATION",
BY MICHAEL SUSKO, SEPTEMBER, 1984.

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AVERAGE CUMULATIVE TOTAL METEOROID FLUX-MASS
MODEL FOR 1 A.U.



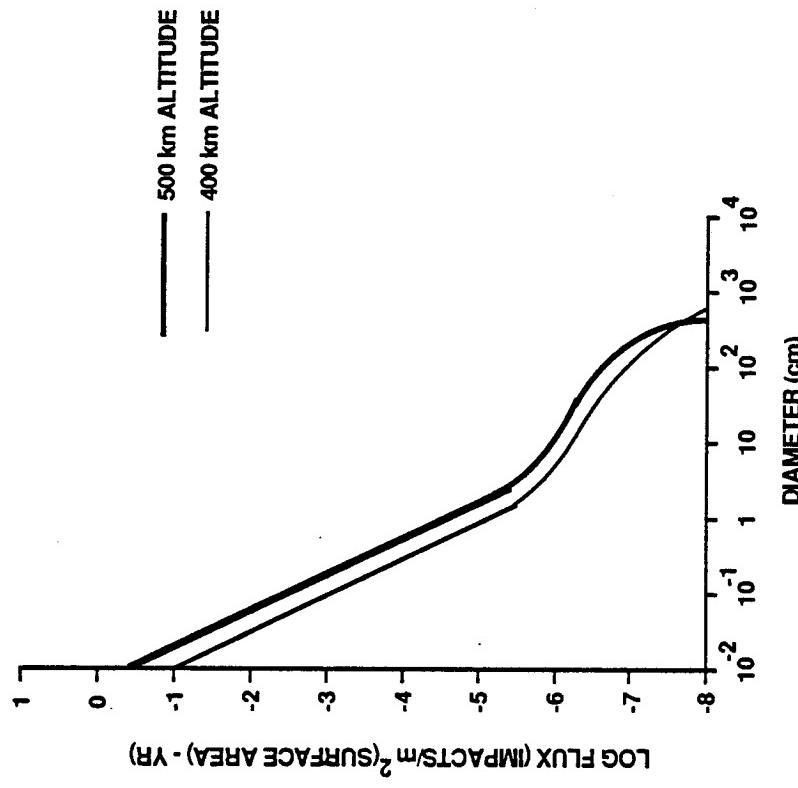
1990's AVERAGE ENVIRONMENT

THE AVERAGE ORBITAL DEBRIS ENVIRONMENT FOR THE 1990's IS SHOWN FOR 400 AND 500 Km ALTITUDES. THIS DATA WAS EXTRACTED FROM JSC-20001, "ORBITAL DEBRIS ENVIRONMENT FOR SPACE STATION", DONALD J. KESSLER. NOTE THE SHARP INFLECTION POINTS OCCURRING AT A DIAMETER OF 1 CM.

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1990's AVERAGE ENVIRONMENT



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SECTION II

**NYSMITH PREDICTOR
APPLIED TO
IDEALIZED SCENARIO**

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WHAT YOU WILL SEE IN SECTION II

- A COMPARISON OF METEOROID AND DEBRIS ENVIRONS FOR THE NYSMITH PREDICTOR-IDEALIZED SCENARIO
- OPTIMAL THICKNESS DISTRIBUTIONS FOR THE NYSMITH PREDICTOR
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
 - BUMPER/WALL SEPARATION
 - PROJECTILE DIAMETER
 - PROJECTILE VELOCITY
 - MISSION RISK
 - MISSION DURATION

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BASELINE DESIGN PARAMETERS

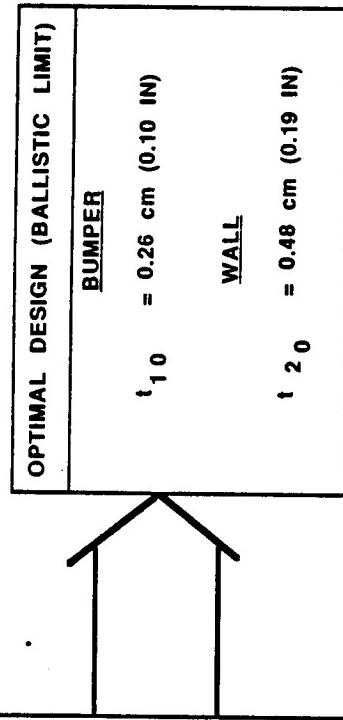
THE MARCH 1987 BASELINE DESIGN PARAMETERS USED FOR ANALYSIS OF THE NYSMITH PREDICTOR ARE SHOWN. THESE PARAMETERS IMPLY A BASELINE OPTIMAL (NYSMITH) DESIGN THAT IS ROUGHLY 1.5 TIMES THE CURRENT DESIGN.

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BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS	
P_0	= 0.97 (PROBABILITY OF NO PENETRATION)
T	= 10 YRS (MISSION DURATION)
A_d	= 574 m ² (DEBRIS AREA)
A_m	= 403 m ² (METEOROID AREA)
Alt	= 500 km (AVERAGE ALTITUDE)
v_m	= 20 km/sec (AVERAGE METEOROID VELOCITY)
v_d	= 10 km/sec (AVERAGE DEBRIS VELOCITY)
ρ_m	= 0.5 gm/cm ³ (METEOROID DENSITY)
ρ_d	= 2.81 gm/cm ³ (DEBRIS DENSITY)
h	= 10 cm (BUMPER/WALL. SEPARATION)



NYSMITH EQUATION
IDEALIZED SCENARIO

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DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

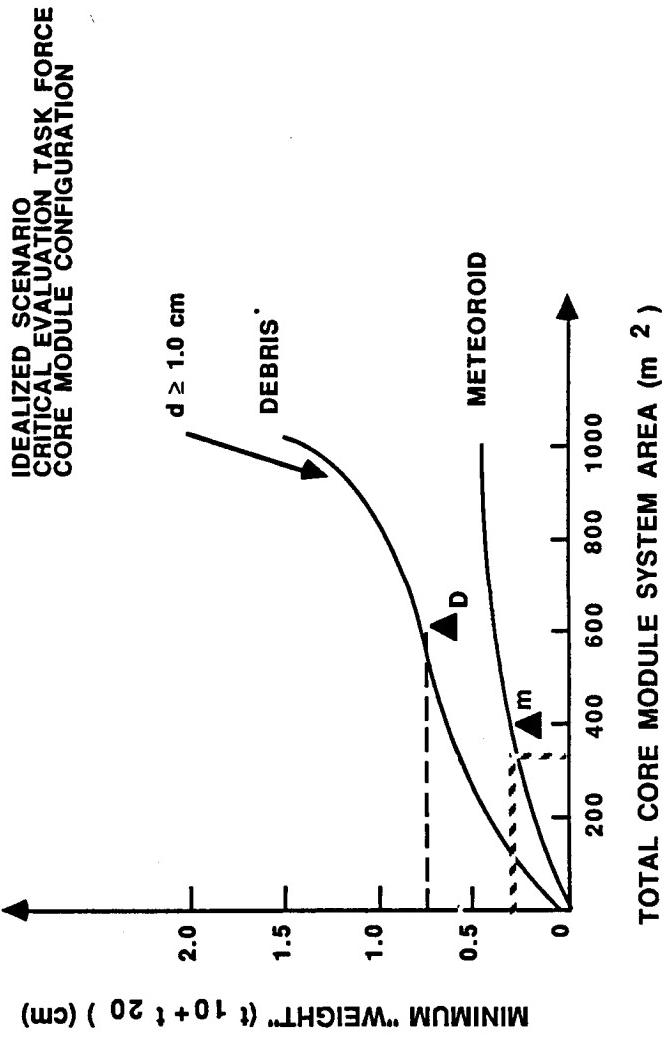
SHOWN IS THE OPTIMAL DESIGN, INDUCED BY THE DEBRIS AND METEOROID ENVIRONS, TAKEN SEPARATELY, FOR VARIOUS CORE MODULE SYSTEM AREAS. THE DEBRIS ENVIRONMENT DRIVES DESIGN FOR ALL SYSTEM AREAS. NOTE THE INFLECTION POINT FOR A SYSTEM AREA OF ROUGHLY 850 SQUARE METERS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE FOR A PARTICLE DIAMETER OF 1 CM. THE EQUIVALENT DEBRIS AREA FOR THE CURRENT DESIGN ("WEIGHT" ~ 0.48 CM) IS ONLY 330 SQUARE METERS.

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DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

EQUIVALENT DEBRIS AREA FOR
CURRENT DESIGN $\approx 330 \text{ m}^2$



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DEBRIS ENVIRONMENT DRIVES DESPITE P_0 REDUCTION

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A R_b OF 0.95 IS ILLUSTRATED. ALTHOUGH THIS REDUCTION IN P_0 REPRESENTS A DRAMATIC REDUCTION IN DESIGN, THE DEBRIS ENVIRONMENT CONTINUES TO DRIVE THE DESIGN.

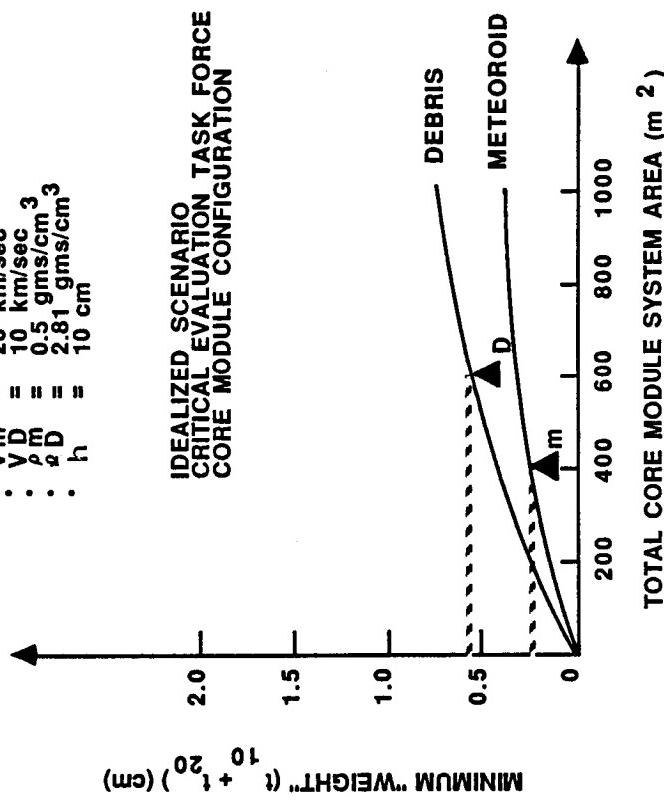
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DEBRIS ENVIRONMENT DRIVES DESPITE PO REDUCTION

P _o	=	0.95
T _{lt}	=	10 YRS
A _{lt}	=	500 km
V _m	=	20 km/sec
V _D	=	10 km/sec
ρ_D	=	0.5 gms/cm ³
ρ_D	=	2.81 gms/cm ³
h	=	10 cm

IDEALIZED SCENARIO
CRITICAL EVALUATION TASK FORCE
CORE MODULE CONFIGURATION



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INCREASE IN P_0 PRODUCES DRAMATIC WEIGHT
INCREASE: BASELINE MISSION NOT REALIZED

SHOWN IS THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A P_0 OF 0.99. CLEARLY, THIS RESULTS IN A SIGNIFICANT INCREASE IN DESIGN TO THE POINT WHERE THE BASELINE SYSTEM AREA CANNOT BE ACHIEVED. THIS IS DUE TO THE FACT THAT THE DESIGN PAR-TICLE INDUCED BY SO LARGE A P_0 EXCEEDS THE LIMITATIONS OF THE THIRD INEQUALITY CONSTRAINT OF NYSMITH.

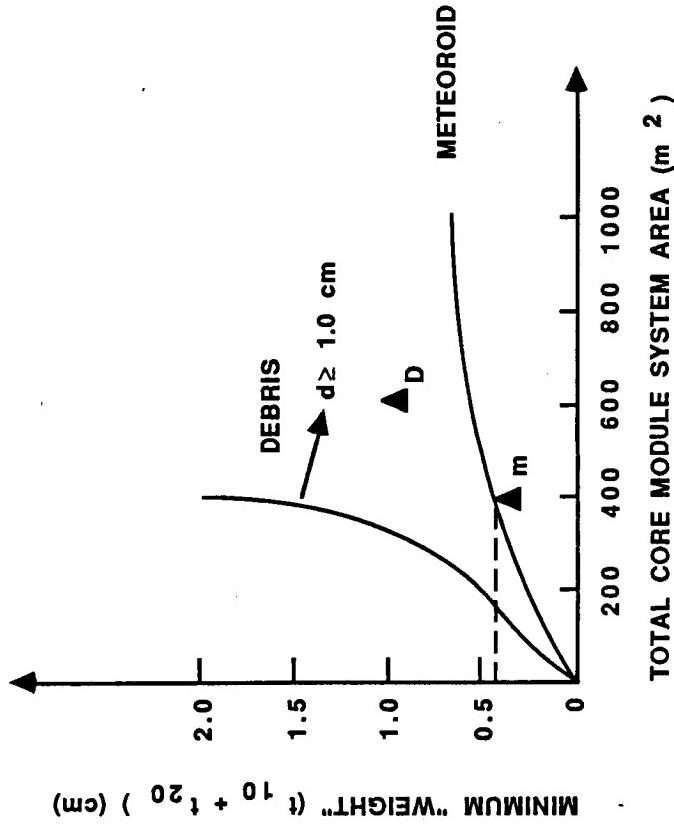
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INCREASE IN P_0 PRODUCES DRAMATIC WEIGHT INCREASE: BASELINE MISSION NOT REALIZED

$$\frac{P_0}{T} = 0.99$$

- A_{lt} = 10 yrs
- V_m = 500 km
- V_D = 20 km/sec
- ρ_m = 10 km/sec
- ρ_D = 0.5 gms/cm³
- ρ_D = 2.81 gms/cm³
- h = 10 cm
- IDEALIZED SCENARIO
- CRITICAL EVALUATION TASK FORCE
- CORE MODULE CONFIGURATION



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MC8 OT 5/87 RWL



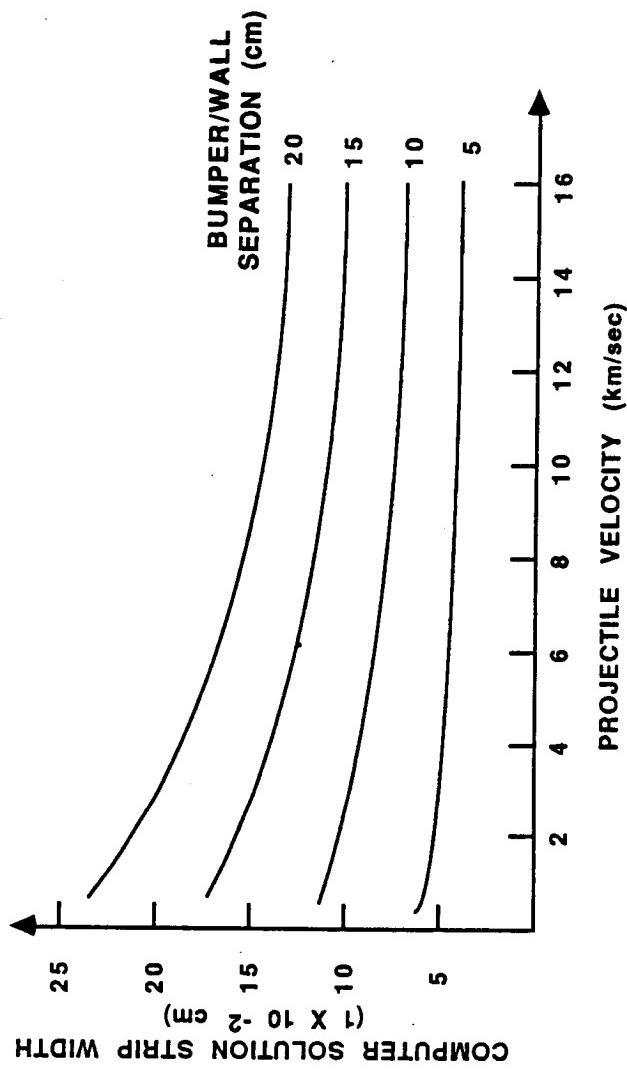
COMPUTER SOLUTION REGION IS NARROW FOR MOST SCENARIOS - NYSMITH EQUATION

SHOWN IS THE WIDTH OF THE COMPUTER SOLUTION REGION FOR THE NYSMITH EQUATION AS A FUNCTION OF PROJECTILE VELOCITY, FOR VARIOUS BUMPER/WALL SEPARATIONS. THIS WIDTH REPRESENTS THE DIFFERENCE IN THE PROJECTILE DIAMETER AT THE BEGINNING OF THE NO SOLUTION REGION AND THE END OF THE ANALYTICAL SOLUTION REGION. CLEARLY, FOR PARAMETERS IN THE NEIGHBORHOOD OF THE BASELINE PARAMETERS, THIS REGION IS VERY NARROW. IN FACT, THE REGION IS NARROW ENOUGH TO BE APPROXIMATED BY THE ANALYTICAL (UNCONSTRAINED) SOLUTION TO THE NYSMITH EQUATION, THUS REDUCING COMPUTER USAGE.

BM14-91

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**COMPUTER SOLUTION REGION IS NARROW
FOR MOST SCENARIOS - NYSMITH EQUATION**



UNCLASSIFIED
MC 9 OT 5/87 RWL

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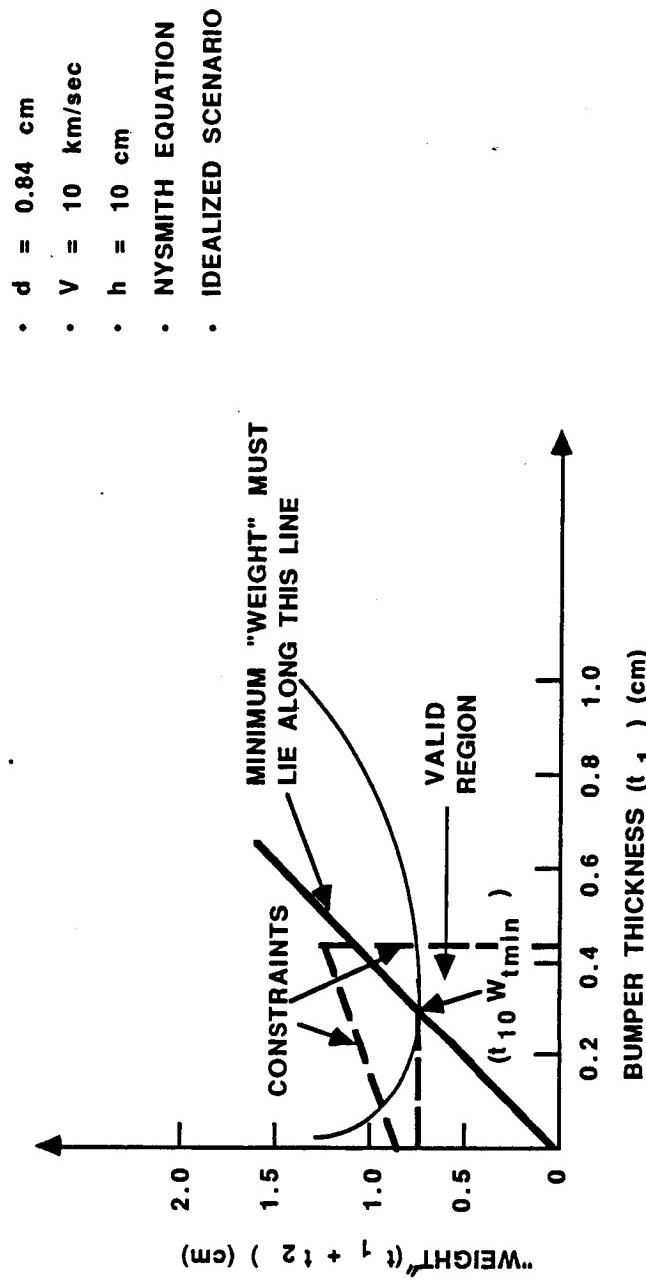
GP METHOD CONFIRMS THE MINIMUM WEIGHT

THE BASIC OPTIMIZATION PROBLEM SOLVED USING GEOMETRIC PROGRAMMING (GP) IS SHOWN. THE INTERSECTION OF THE SOLID LINE AND CURVE OCCURS AT THE GLOBAL MINIMUM, VERIFYING THE GP METHODOLOGY. NOTE THAT THE MINIMUM "WEIGHT" LINE DOES NOT INTERSECT THE INTERSECTION OF THE INEQUALITY CONSTRAINTS. THIS OFFSET ESTABLISHES THE COMPUTER SOLUTION REGION AS DISCUSSED EARLIER.

BM15-9/1



GP METHOD CONFIRMS THE MINIMUM WEIGHT



UNCLASSIFIED
MC10 OT 5/87 RWL

SAIC

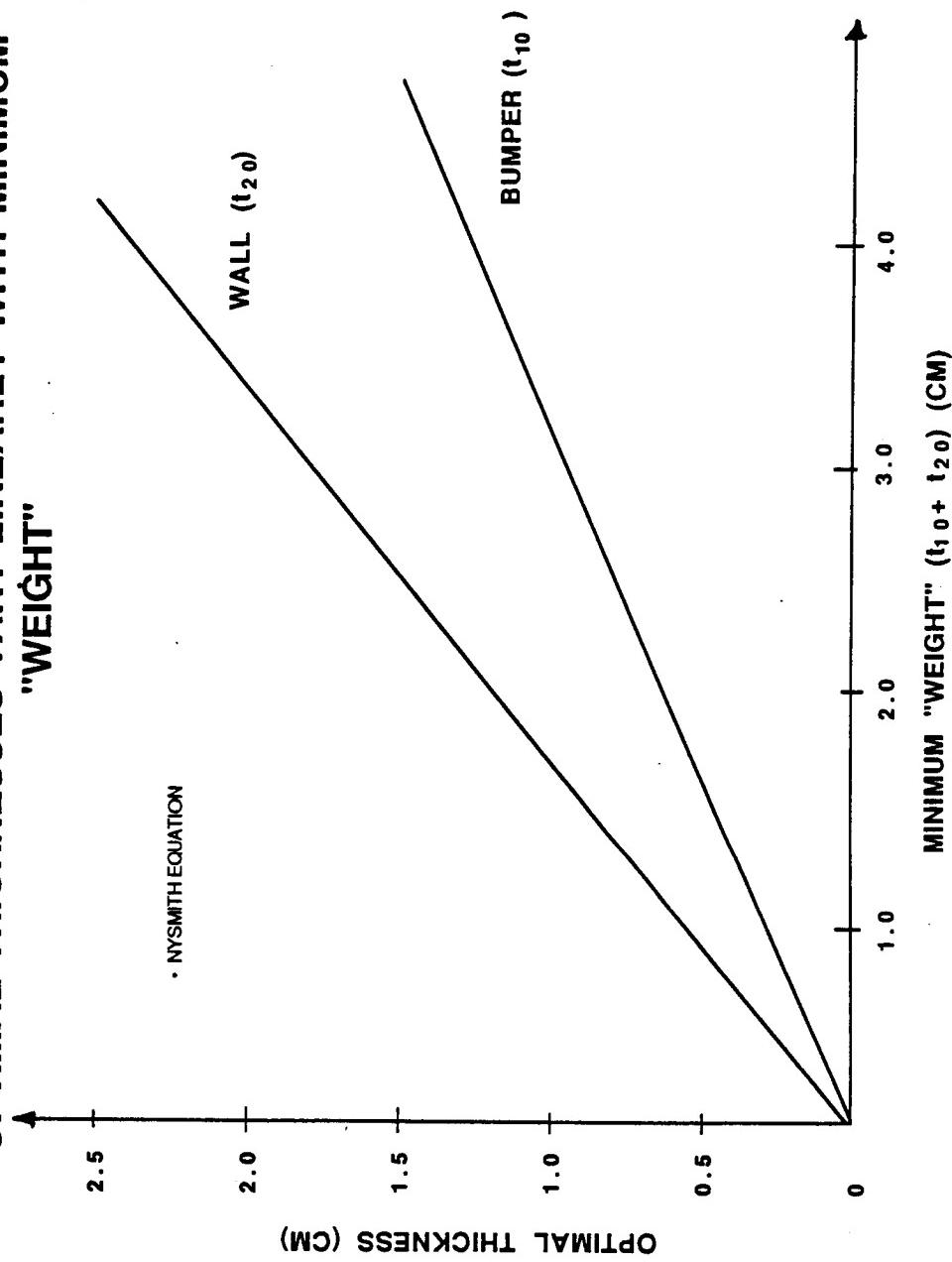
OPTIMAL THICKNESSES VARY LINEARLY
WITH "MINIMUM WEIGHT"

SHOWN ARE THE LINEAR RELATIONSHIPS BETWEEN THE OPTIMAL THICKNESSES OF THE BUMPER AND WALL AND THE MINIMUM "WEIGHT" AS REPRESENTED BY THE SUM OF BUMPER AND WALL THICKNESSES. THE LINES, EMANATING FROM THE ORIGIN, HAVE SLOPES OF 0.35 AND 0.65 FOR THE BUMPER AND WALL, RESPECTIVELY.

BMI6-91



**OPTIMAL THICKNESSES VARY LINEARLY WITH MINIMUM
"WEIGHT"**



2OTR8K

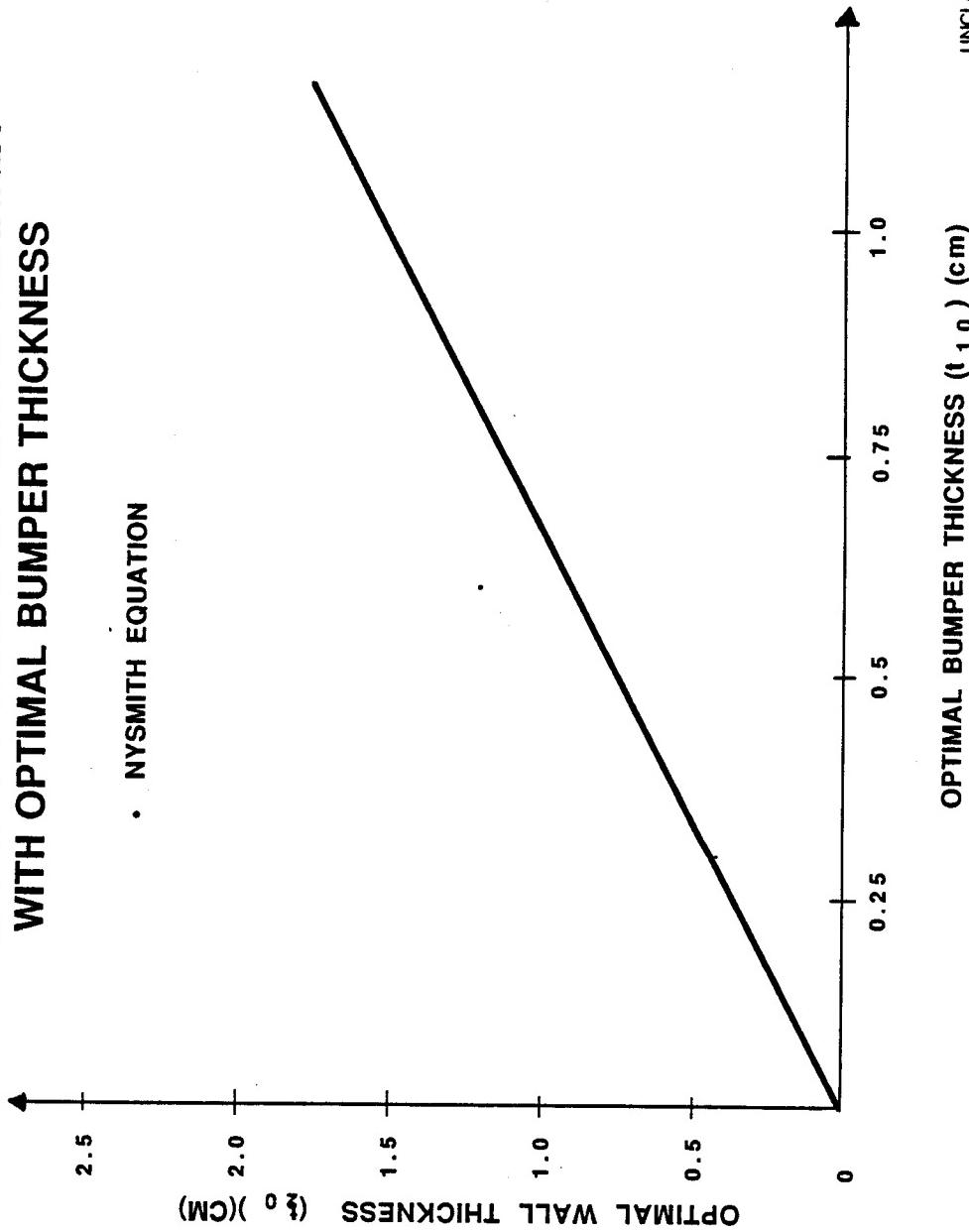
SAICTM

**OPTIMAL WALL THICKNESS VARIES LINEARLY
WITH OPTIMAL BUMPER THICKNESS**

SHOWN IS THE LINEAR RELATIONSHIP BETWEEN THE OPTIMAL WALL THICKNESS AND THE OPTIMAL BUMPER THICKNESS FOR THE NYSMITH PREDICTOR. THE LINE EMANATES FROM THE ORIGIN AND HAS A SLOPE OF APPROXIMATELY 1.92.

OPTIMAL WALL THICKNESS VARIES LINEARLY
WITH OPTIMAL BUMPER THICKNESS

• NYSMITH EQUATION



UNCLASSIFIED
MC11 OT RWL

~~SALE~~

OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

THIS SET OF CURVES SHOWS THE EFFECT OF BUMPER/WALL SEPARATION ON OPTIMAL DESIGN FOR THE NYSMITH PREDICTOR. NOTE THE HIGH PAY-OFF FOR INCREASING THIS SEPARATION UP TO ABOUT 15 CM, WHICH, INCIDENTALLY, CORRESPONDS TO THE CORE MODULE VOLUME CONSTRAINT FOR SHUTTLE PAYLOADS. FINALLY, TOWARD THE LEFT OF THE THREE CURVES LIE THE CONSTRAINTS IMPOSED ON THIS SEPARATION BY THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION. NOTE THAT THESE POINTS LIE ON A STRAIGHT LINE THROUGH THE ORIGIN, AND THE REGION TO THE LEFT OF THIS LINE IS INFEASIBLE.

BM18-91



OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

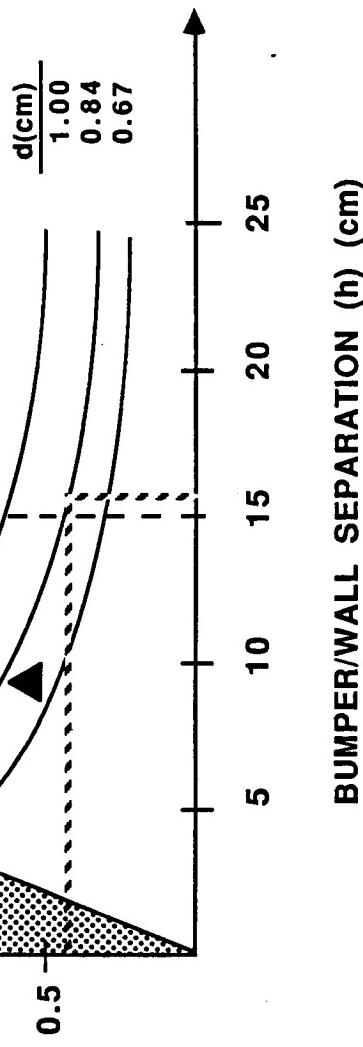
- $V = 10 \text{ km/sec}$
- Nysmith Equation
- Idealized Scenario

CORE MODULE
VOLUME CONSTRAINT

THIRD INEQUALITY
CONSTRAINT OF
NYSMITH

MINIMUM "WEIGHT" ($t_{10} + t_{20}$) (cm)

Equivalent Separation for Current
Design $\approx 17 \text{ cm}$

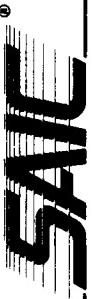


GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN

ONE IMPORTANT SENSITIVITY ANALYSIS IS THE EFFECT OF THREAT, IN TERMS OF SPACE DEBRIS PROJECTILE DIAMETER, ON OPTIMAL DESIGN.

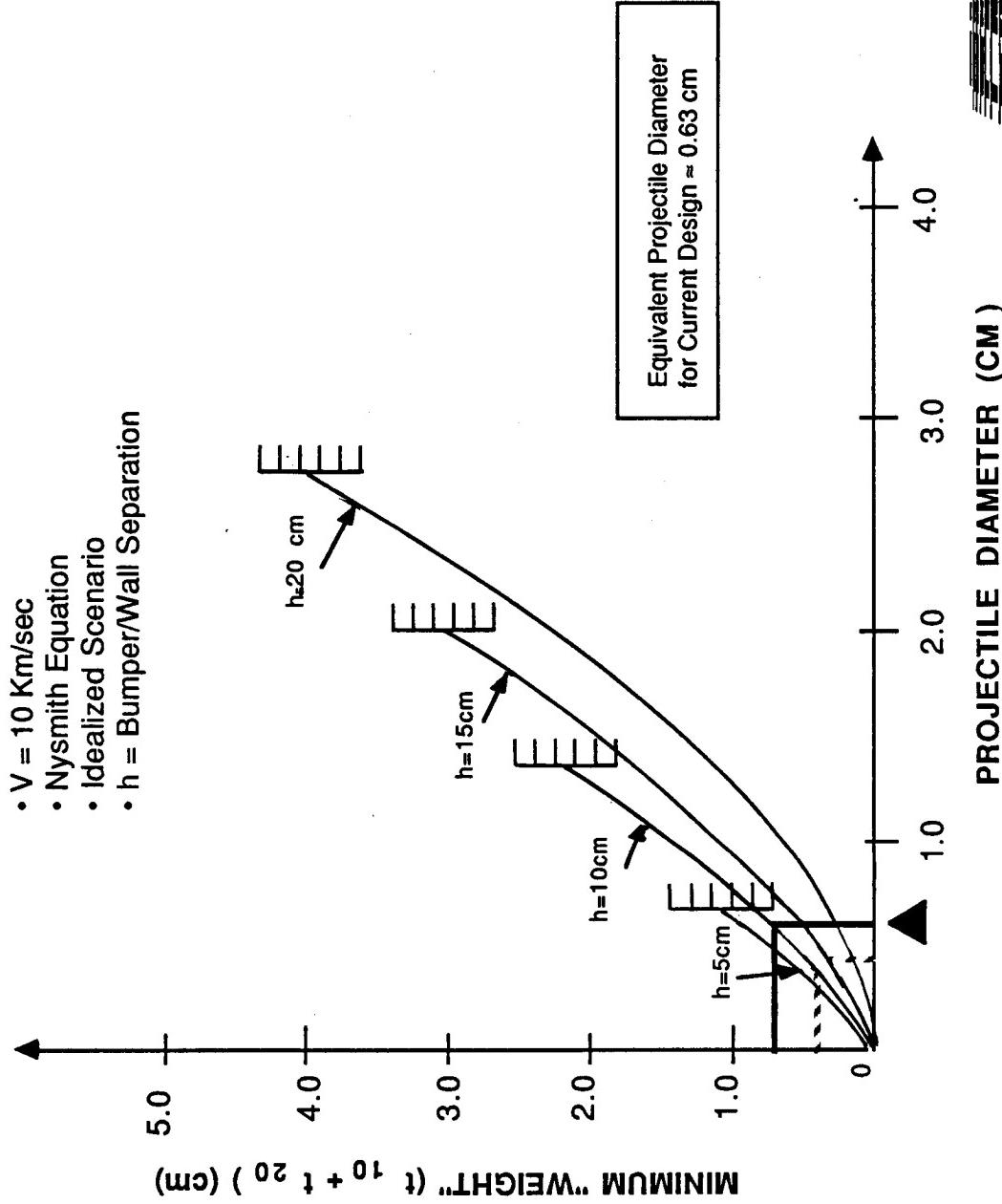
THE EFFECT OF PROJECTILE DIAMETER ON "WEIGHT" IS SHOWN FOR VARIOUS BUMPER/WALL SEPARATIONS. THE EQUIVALENT PROJECTILE DIAMETER INDUCED BY THE CURRENT DESIGN IS ROUGHLY 0.63 CM. THE LIMITS IMPOSED ON PROJECTILE DIAMETER BY THE THIRD INEQUALITY CONSTRAINT FOR EACH CURVE ARE SHOWN TO THE RIGHT. AGAIN, THESE CURVES LIE ON A STRAIGHT LINE THROUGH THE ORIGIN.

BM19-9/1



GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN

- $V = 10 \text{ Km/sec}$
- Nyssmith Equation
- Idealized Scenario
- $h = \text{Bumper/Wall Separation}$



Equivalent Projectile Diameter
for Current Design $\approx 0.63 \text{ cm}$

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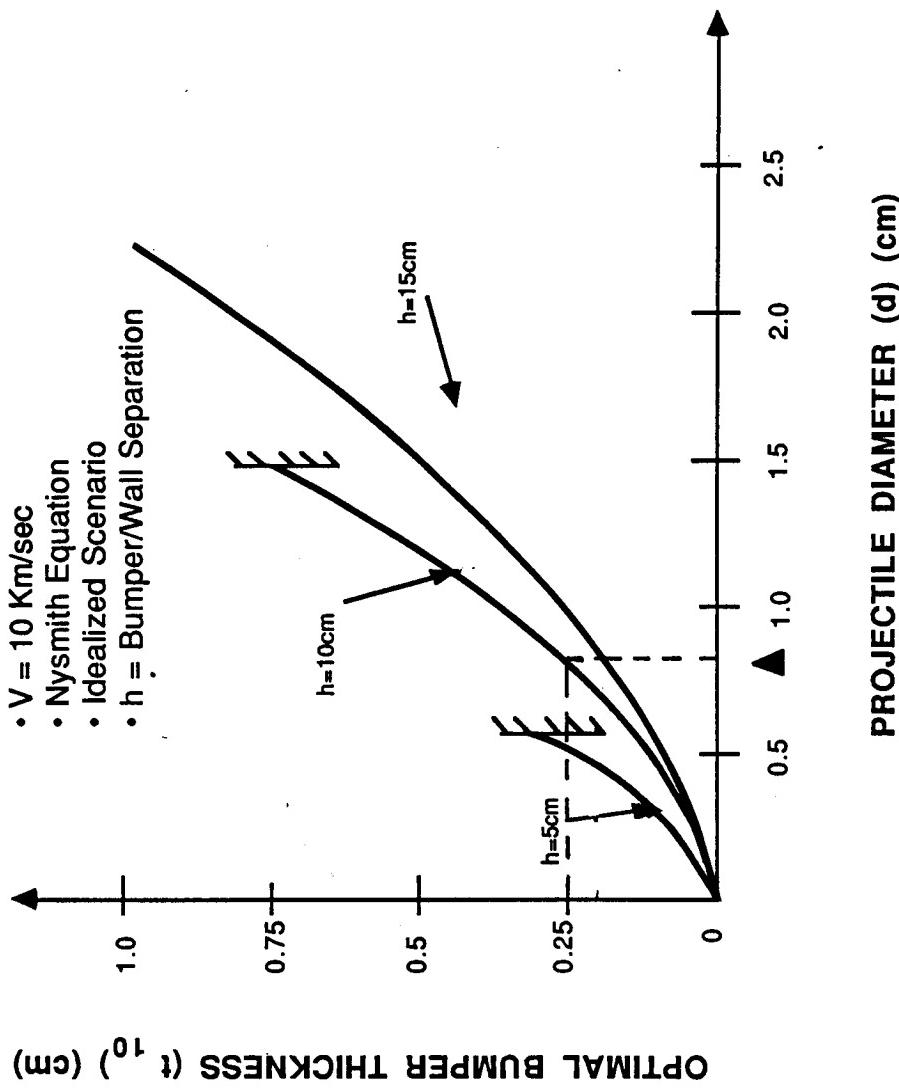
OPTIMAL DESIGN IS SENSITIVE TO THREAT

THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS IS SHOWN. A 20% INCREASE IN DIAMETER ABOVE THE BASELINE REQUIRES A 40% INCREASE IN OPTIMAL BUMPER THICKNESS.

BM20-9/1



OPTIMAL DESIGN IS SENSITIVE TO THREAT



SAC

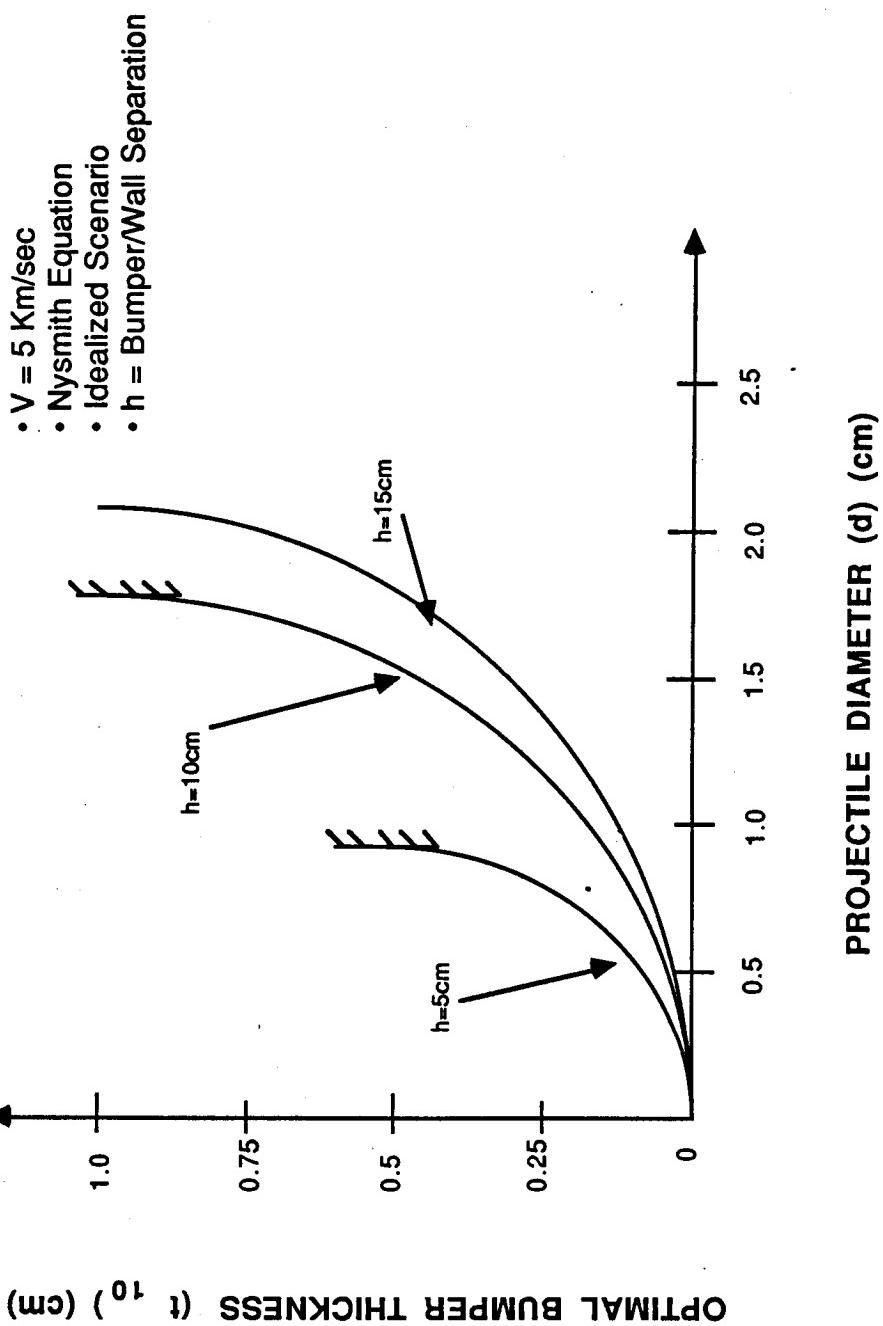
OPTIMAL DESIGN IS SENSITIVE TO THREAT

**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER
THICKNESS FOR A PROJECTILE VELOCITY OF 5 KM/SEC IS
SHOWN.**

BM21-9/1



OPTIMAL DESIGN IS SENSITIVE TO THREAT

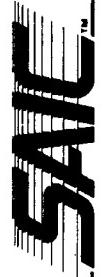


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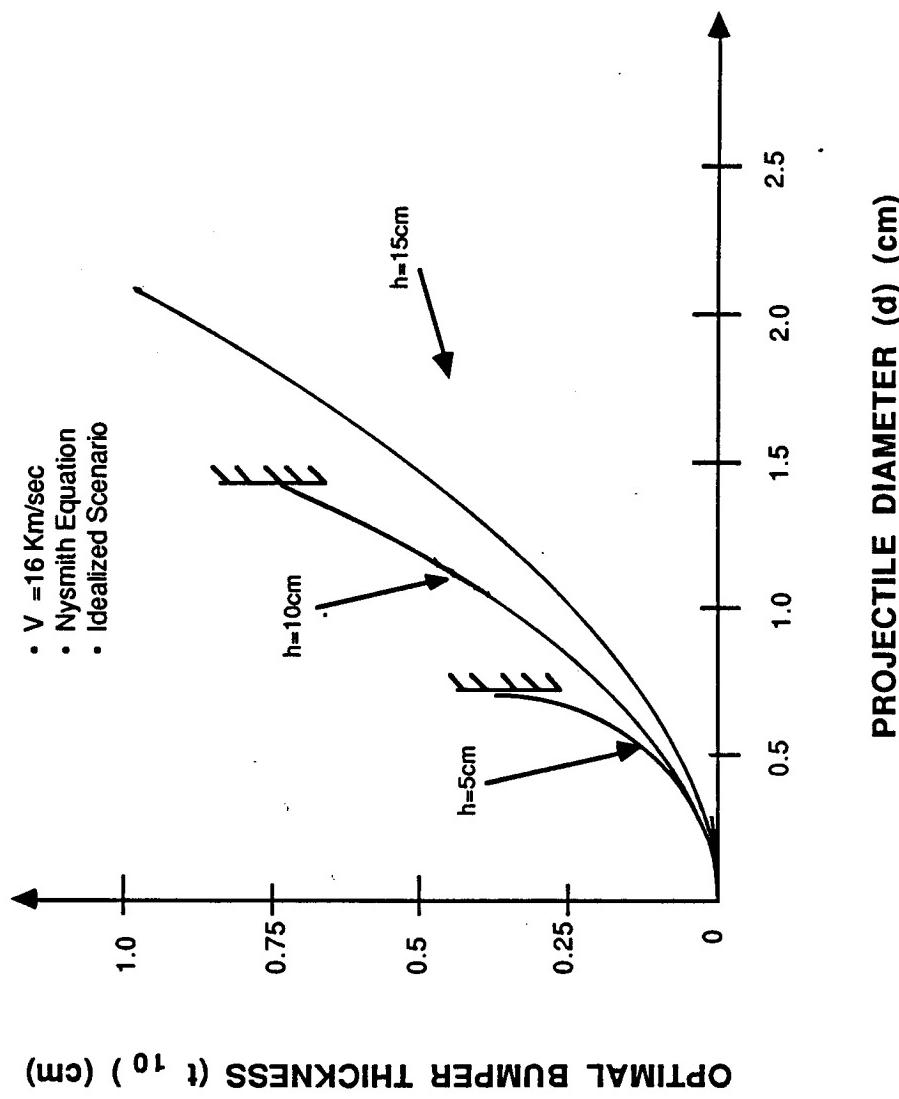
OPTIMAL DESIGN IS SENSITIVE TO THREAT

**THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER
THICKNESS FOR A PROJECTILE VELOCITY OF 16 KM/SEC IS
SHOWN.**

BM22.91



OPTIMAL DESIGN IS SENSITIVE TO THREAT



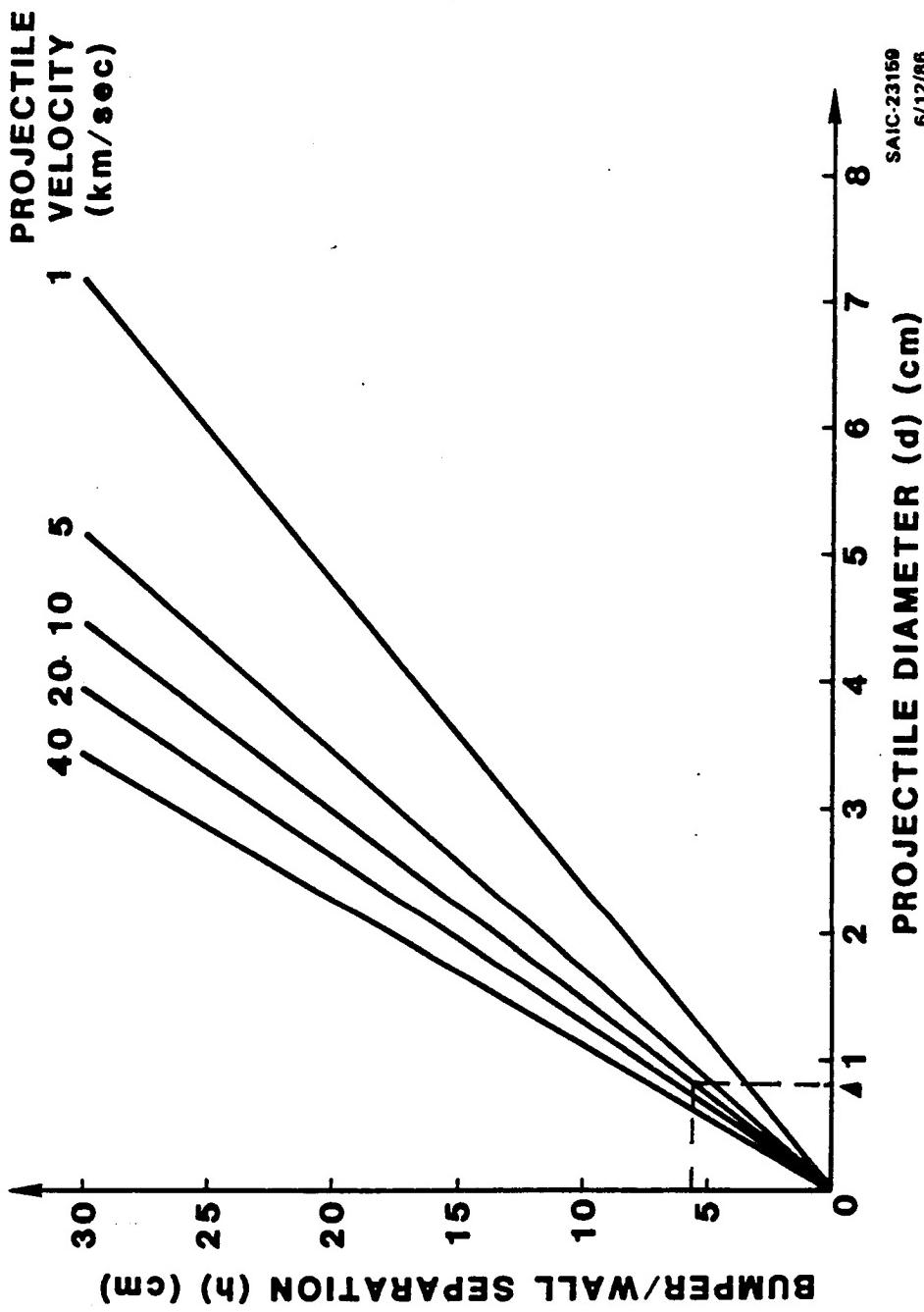
**GP METHOD PROVIDES THE MINIMUM BUMPER/WALL
SEPARATION REQUIRED FOR VARIOUS THREAT SCENARIOS**

THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION IN TERMS
OF THE MINIMUM BUMPER/WALL SEPARATION AS A FUNCTION OF PROJECTILE
DIAMETER FOR VARIOUS PROJECTILE VELOCITIES IS SHOWN. THE BASELINE
MINIMUM SEPARATION ALLOWED IS ROUGHLY 6 CM.

BM23-9/1



**GP METHOD PROVIDES THE MINIMUM BUMPER/WALL
SEPARATION REQUIRED FOR VARIOUS THREAT SCENARIOS**



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6/12/86

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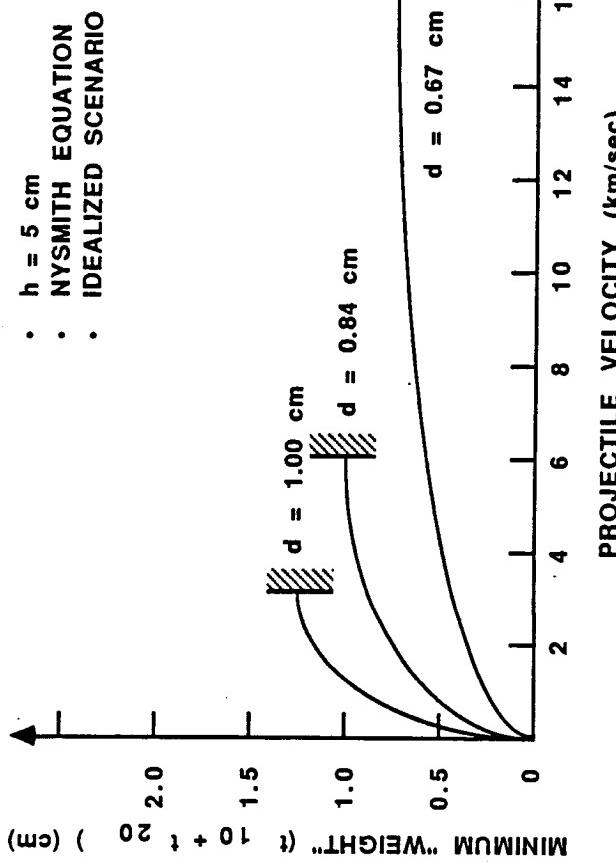
OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

THE NEXT THREE TRADE SETS SHOW THE EFFECT OF PROJECTILE VELOCITY ON DESIGN FOR VARIOUS PROJECTILE DIAMETERS, FOR 5, 10, AND 15 CM BUMPER/WALL SEPARATIONS. IN THE HIGHER VELOCITY (5-16 KM/SEC) PORTIONS OF THESE CURVES, THE DESIGN REMAINS RELATIVELY INSENSITIVE TO PROJECTILE VELOCITY. NOTE THAT THE EQUIVALENT PROJECTILE VELOCITY INDUCED BY THE CURRENT DESIGN IS 2.5 KM/SEC.

BM24-91

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OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS



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MC 12 OT 5/87 RWL

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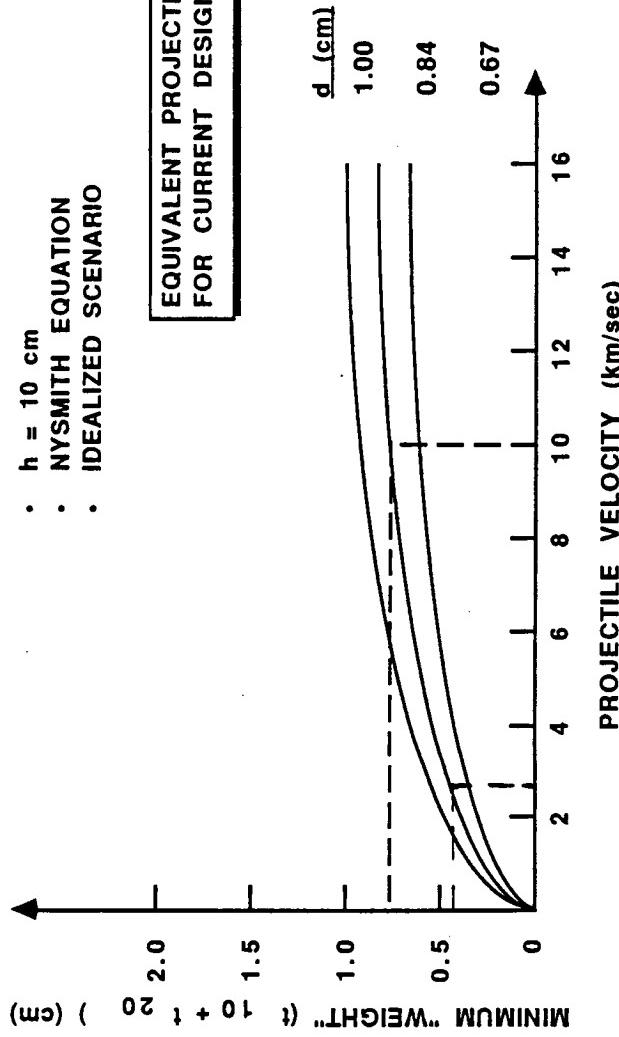
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OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

- $h = 10 \text{ cm}$
- NYSMITH EQUATION
- IDEALIZED SCENARIO

EQUIVALENT PROJECTILE VELOCITY
FOR CURRENT DESIGN ~ 2.5 km/sec



UNCLASSIFIED
MC 13 OT 5/87 RWL

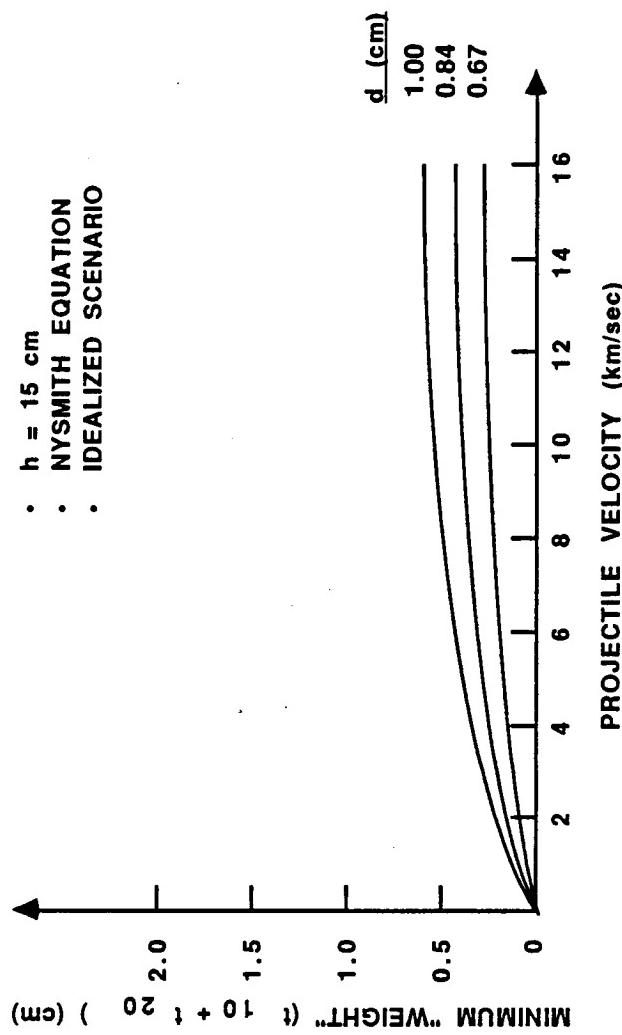
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OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE VELOCITY IN HIGH VELOCITY REGIONS

- $h = 15 \text{ cm}$
- NYSMITH EQUATION
- IDEALIZED SCENARIO



UNCLASSIFIED
MC 14 OT 5/87 RWL

SAIC

OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR P_0 ABOVE 0.97

THE EFFECT OF DESIGN ON ACCEPTABLE MISSION RISK FOR VARIOUS SPACECRAFT DEBRIS AREAS, AND FOR VARIOUS BUMPER/WALL SEPARATIONS IS SHOWN IN THE NEXT THREE CHARTS. MISSION RISK PLAYS A VERY SIGNIFICANT ROLE IN DETERMINING THE OPTIMAL DESIGN. NOTE THAT THE EQUIVALENT MISSION RISK INDUCED BY THE CURRENT DESIGN IS 5.8%, CORRESPONDING TO A P_0 OF 0.942.

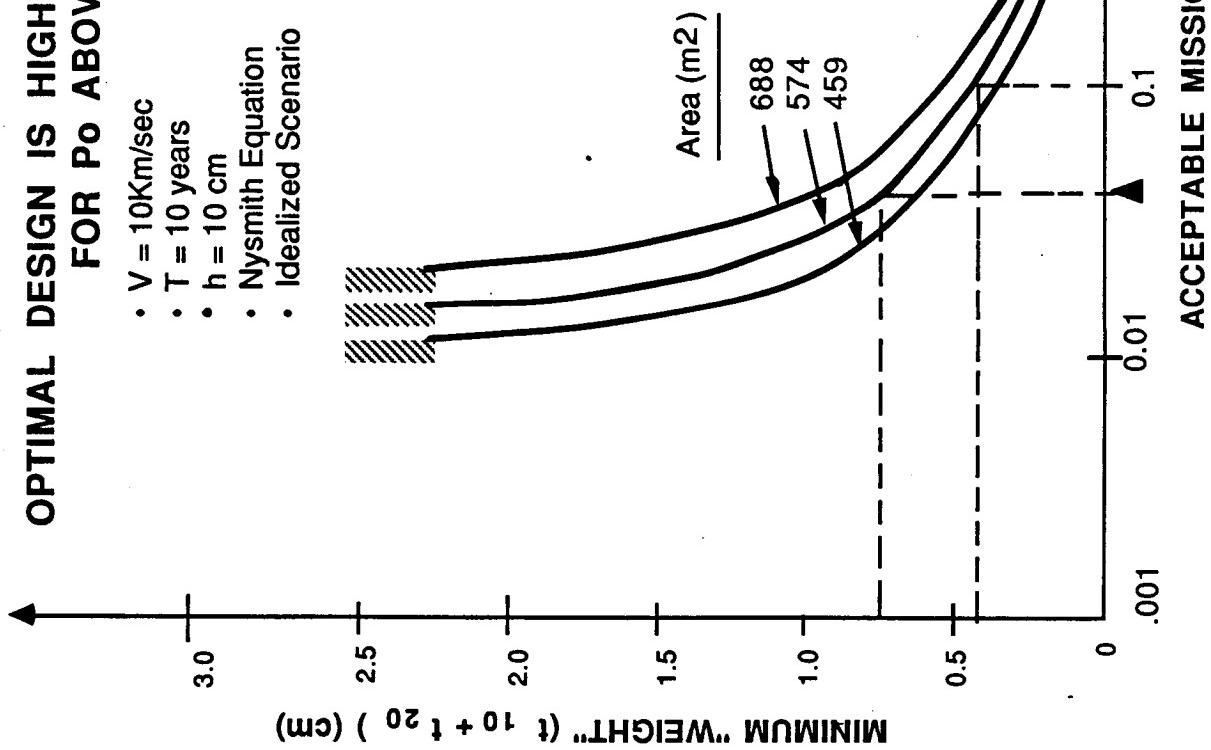
BM25-9/1



**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK
FOR P_o ABOVE 0.97**

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ years}$
- $h = 10 \text{ cm}$
- Nysmith Equation
- Idealized Scenario

EQUIVALENT MISSION RISK
FOR CURRENT DESIGN ~ 5.8%
($P_o \sim .942$)

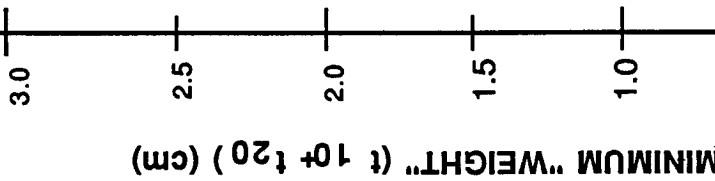


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SALE

**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK
FOR P_o ABOVE 0.97**

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ years}$
- $h = 5 \text{ cm}$
- Nysmith Equation
- Idealized Scenario



DATA

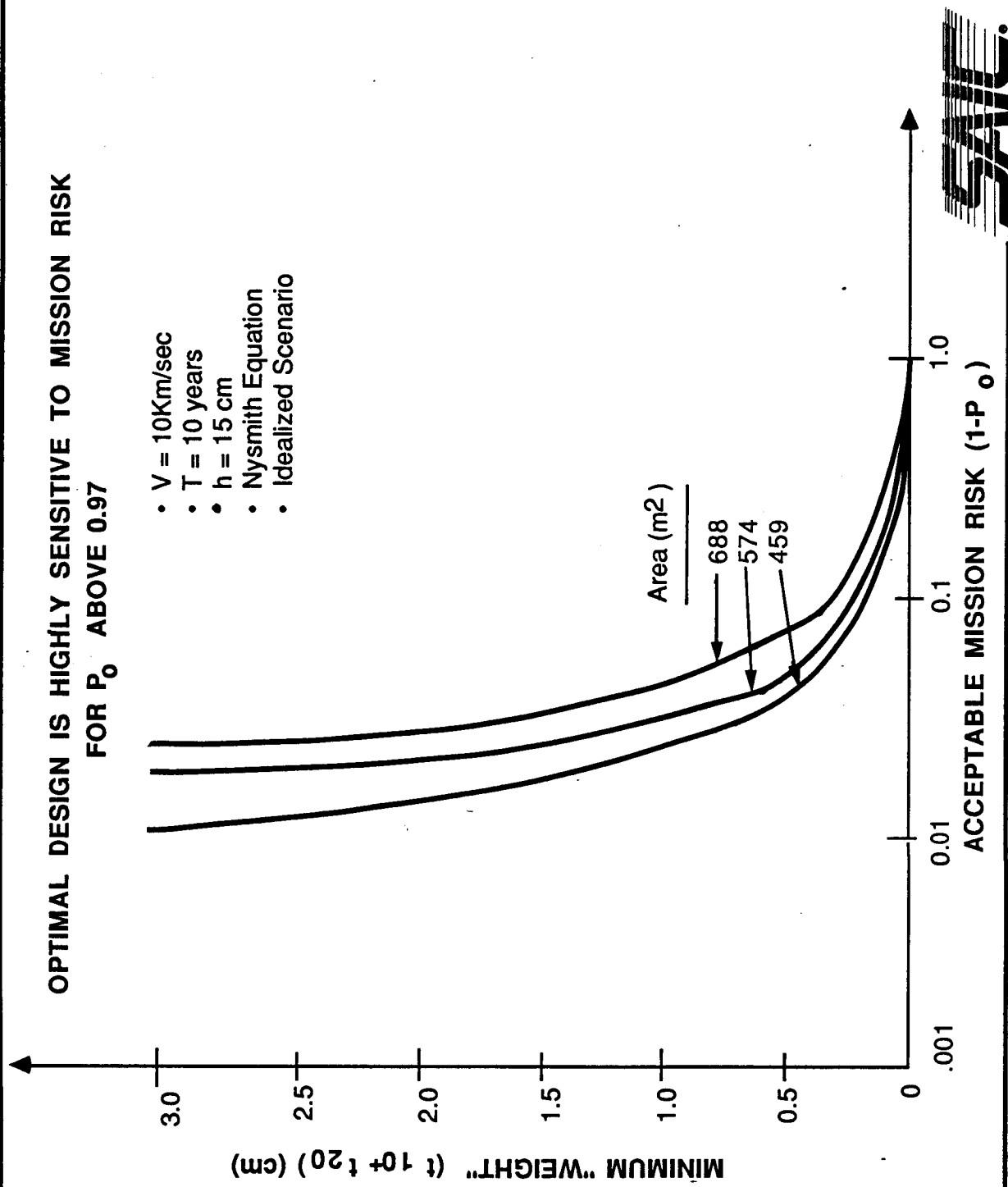
ACCEPTABLE MISSION RISK ($1 - P_o$)

SAIC

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**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK
FOR P_0 ABOVE 0.97**

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ years}$
- $h = 15 \text{ cm}$
- Nysmith Equation
- Idealized Scenario



OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

THE NEXT TWO SETS OF TRADES SHOW, FOR DIFFERENT P_0 's, THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR VARIOUS SPACECRAFT DEBRIS AREAS. NOTE THE HIGH SENSITIVITY, EVEN INFLECTION IN SOME CASES, OCCURRING IN THE 10-30 YEAR RANGE. THE INFLECTION IS DUE TO THE INFLECTION IN THE SPACE DEBRIS ENVIRONMENT CURVE AT 1 CM DIAMETER PARTICLES. THE EQUIVALENT MISSION DURATION FOR THE CURRENT DESIGN IS ROUGHLY 5.5 YEARS.

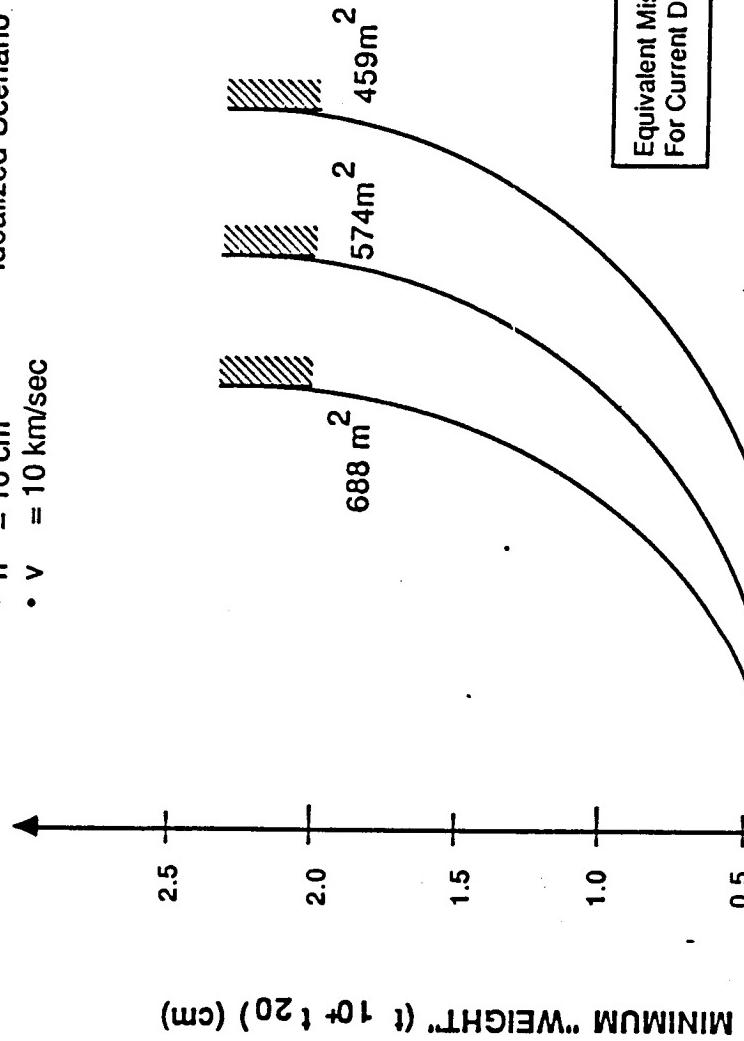
BM26-9/1



OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN 10-30 YEAR REGION

- $P_0 = 0.97$
- $h = 10 \text{ cm}$
- $v = 10 \text{ km/sec}$

Nyquist Equation
Idealized Scenario



Equivalent Mission Duration
For Current Design ~ 5 1/2 yrs



MISSION DURATION ($T \text{ (yrs)}$)

SAC

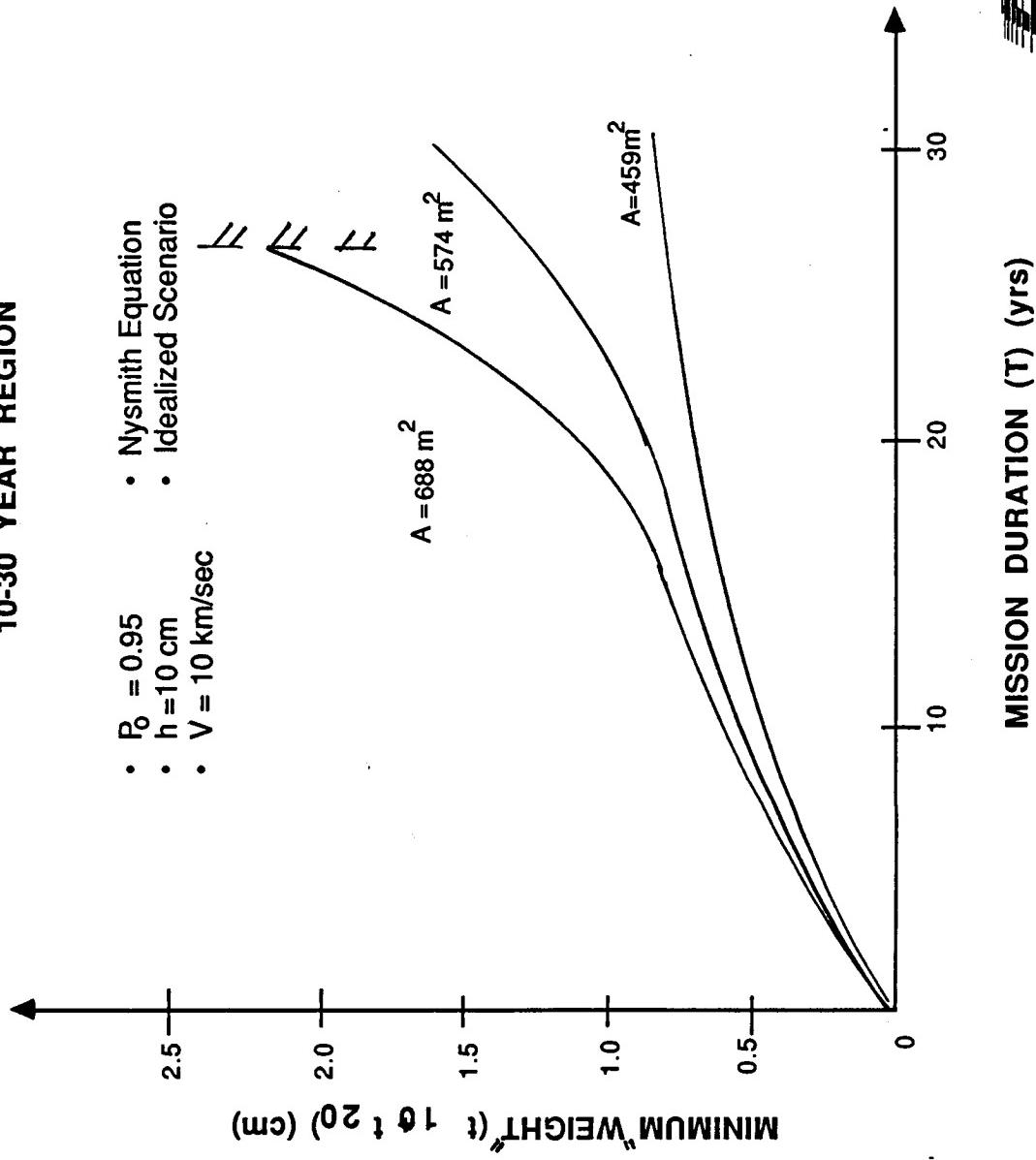
SAVE

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**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN
10-30 YEAR REGION**

- $P_0 = 0.95$
- $h = 10 \text{ cm}$
- $V = 10 \text{ km/sec}$

Nysmith Equation
Idealized Scenario



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SAVE

SECTION III

NYSMITH PREDICTOR
APPLIED TO
CORE MODULE CONFIGURATION

BM40-91



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WHAT YOU WILL SEE IN SECTION III

- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE NYSMITH PREDICTOR APPLIED TO THE CORE MODULE CONFIGURATION
- DESIGN TRADES, INCLUDING MINIMUM WEIGHT VERSUS:
 - BUMPER/WALL SEPARATION
 - PROJECTILE DIAMETER
 - PROJECTILE VELOCITY
 - MISSION RISK
 - MISSION DURATION

BM3 10/13



BASELINE CORE MODULE CONFIGURATION

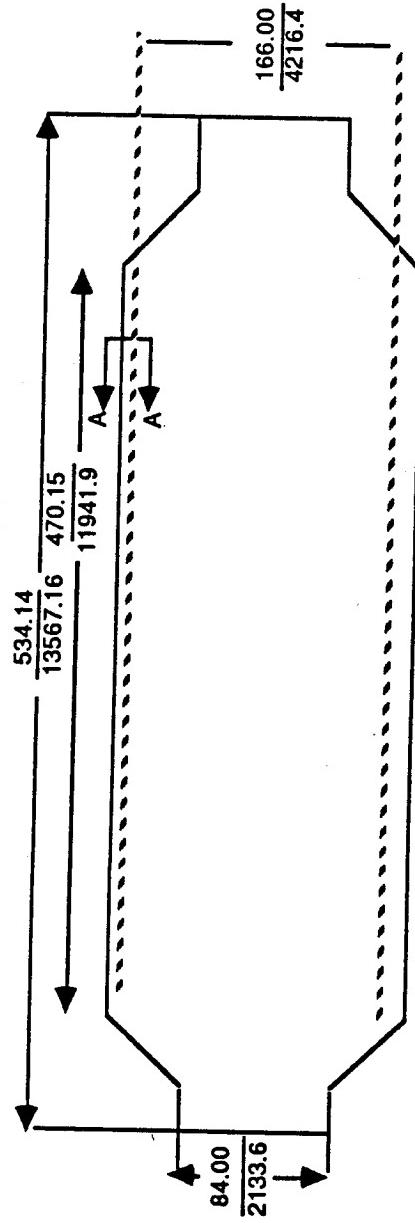
**SHOWN IS THE MARCH 1987 CORE MODULE CONFIGURATION. THIS
IS USED TO OBTAIN THE OBJECTIVE FUNCTION WHICH ESTIMATES
ITS WEIGHT.**

BM27/91



SPACER

BASELINE CORE MODULE CONFIGURATION



• TOP DIMENSIONS IN INCHES

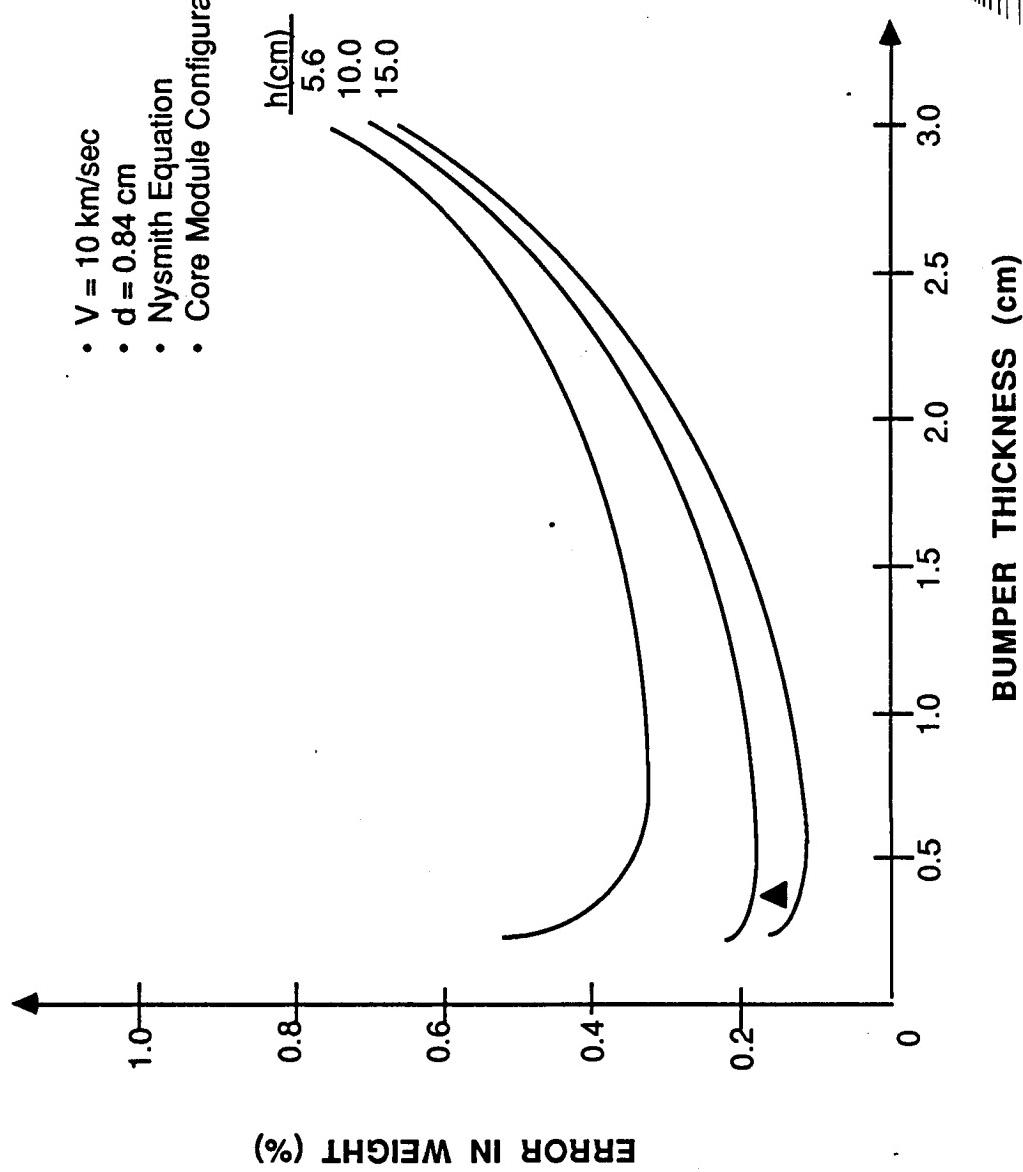
• BOTTOM DIMENSIONS IN MILLIMETERS

**DESIGN ERROR INDUCED BY REDUCING PROBLEM
DEGREE-OF-DIFFICULTY IS NEGLIGIBLE**

SHOWN IS THE ERROR IN THE CORE MODULE CONFIGURATION WEIGHT AS A FUNCTION OF BUMPER THICKNESS FOR VARIOUS BUMPER/WALL SEPARATIONS. THIS REPRESENTS THE ERROR INDUCED BY REDUCING THE OPTIMIZATION PROBLEM DEGREE-OF-DIFFICULTY FROM 5 TO 2. THIS ERROR WILL BE NEGLECTIBLE PROVIDED THE BUMPER AND WALL THICKNESSES ARE SMALL IN COMPARISON TO THE MODULE RADIUS. THE MATHEMATICS BEHIND THIS REDUCTION IN DEGREE-OF-DIFFICULTY IS GIVEN IN APPENDIX A.

**DESIGN ERROR INDUCED BY REDUCING PROBLEM
DEGREE-OF-DIFFICULTY IS NEGLIGIBLE**

- $V = 10 \text{ km/sec}$
- $d = 0.84 \text{ cm}$
- Nysmith Equation
- Core Module Configuration



BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS ARE REFERENCED. THE OPTIMAL DESIGN IS ALMOST EXACTLY THE SAME AS THAT FOUND USING THE IDEALIZED SCENARIO AS THE OBJECTIVE FUNCTION. THIS, COMBINED WITH THE PRECEDING ERROR SHEET, MAKES IT DESIRABLE TO DETERMINE THE OPTIMAL DESIGN VALUES FROM THE IDEALIZED SCENARIO, AND THEN EVALUATE THE CORE MODULE CONFIGURATION WEIGHT USING THOSE VALUES. NOTE THAT THE BASELINE WEIGHT IS ROUGHLY 3800 Kg, OR 8400 LBS.

BM01-8/31



BASELINE DESIGN PARAMETERS

DESIGN	PARAMETERS
P_0	= 0.97
T	= 10 yrs
A_d	= 574 m^2
A_m	= 403 m^2
Alt	= 500 km
v_m	= 20 km/sec
v_D	= 10 km/sec
ρ_m	= 0.5 gm/cm ³
ρ_D	= 2.81 gm/cm ³
h	= 10 cm
NYSMITH EQUATION	

OPTIMAL DESIGN (BALLISTIC LIMIT)	
BUMPER	
t_{10}	= 0.26 cm (0.10 IN)
WALL	
t_{20}	= 0.48 cm (0.19 IN)
WEIGHT	$\approx 3800 \text{ Kg}$ (8400 lbs)

UNCLASSIFIED
MC5 OT 5/87 RWL



DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

THE OPTIMAL DESIGN, INDUCED BY THE DEBRIS AND METEOROID ENVIRONS, TAKEN SEPARATELY, FOR VARIOUS CORE MODULE SYSTEM AREAS IS SHOWN. THE DEBRIS ENVIRONMENT DOMINATES THAT OF THE METEOROID FOR ALL SYSTEM AREAS. NOTE THE INFLECTION POINT FOR A SYSTEM AREA OF ROUGHLY 850 SQUARE METERS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE FOR A PARTICLE DIAMETER OF 1 CM.

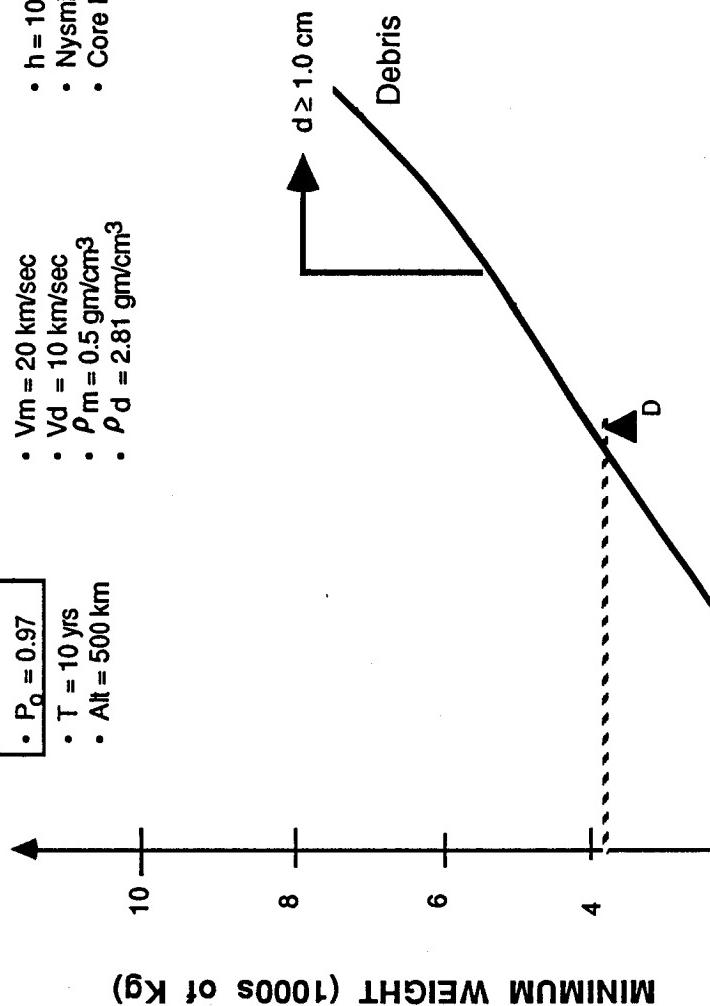
BM29-9/1



DEBRIS ENVIRONMENT DRIVES FOR BASELINE CORE MODULE AREAS

$$\boxed{\begin{array}{l} P_0 = 0.97 \\ T = 10 \text{ yrs} \\ Alt = 500 \text{ km} \end{array}}$$

- $V_m = 20 \text{ km/sec}$
- $V_d = 10 \text{ km/sec}$
- $\rho_m = 0.5 \text{ gm/cm}^3$
- $\rho_d = 2.81 \text{ gm/cm}^3$
- $h = 10 \text{ cm}$
- Nysmith Equation
- Core Module Configuration



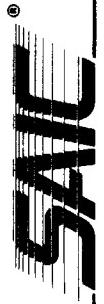
STAGE

TOTAL CORE MODULE SYSTEM AREA (m^2)

DEBRIS ENVIRONMENT DRIVES DESPITE P_0 REDUCTION

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A P_0 OF 0.95 IS SHOWN. ALTHOUGH THIS REDUCTION IN P_0 REPRESENTS A DRAMATIC REDUCTION IN DESIGN, THE DEBRIS ENVIRONMENT CONTINUES TO DRIVE THE DESIGN.

BM30-9/1



DEBRIS ENVIRONMENT DRIVES DESPITE P_0 REDUCTION

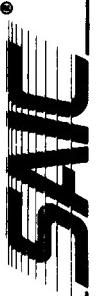


SPAC

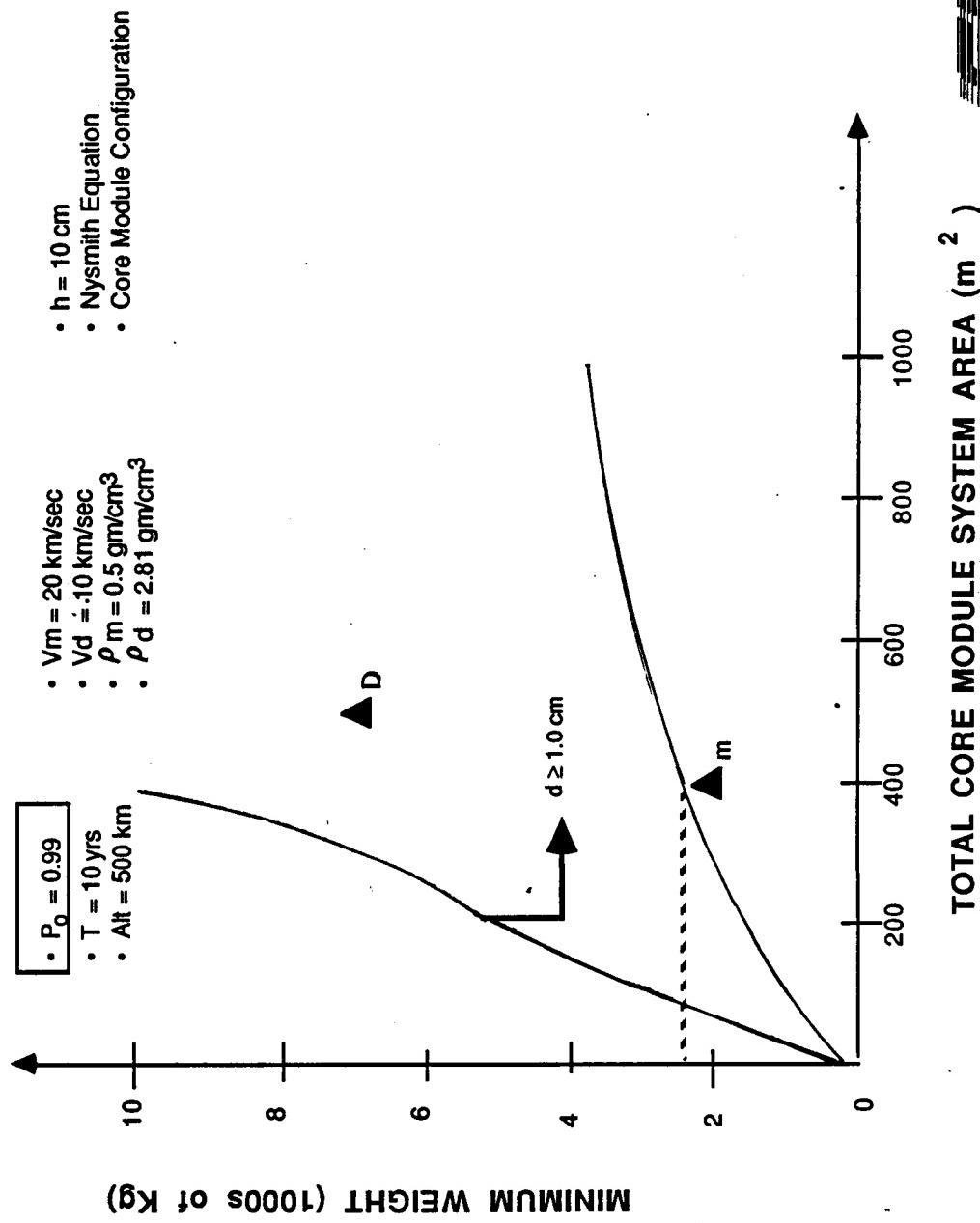
**INCREASE IN P_0 PRODUCES DRAMATIC WEIGHT INCREASE:
BASELINE MISSION NOT REALIZED.**

THE OPTIMAL DESIGN INDUCED BY THE DEBRIS AND METEOROID ENVIRONS FOR A P_0 OF 0.99 IS SHOWN. CLEARLY, THIS RESULTS IN A SIGNIFICANT INCREASE IN DESIGN TO THE POINT WHERE THE BASELINE SYSTEM AREA CANNOT BE ACHIEVED. THIS IS DUE TO THE FACT THAT THE DESIGN PARTICLE INDUCED BY SO LARGE A P_0 EXCEEDS THE LIMITATIONS OF THE THIRD INEQUALITY CONSTRAINT OF NYSMITH.

BM13.9/1



**INCREASE IN P_0 PRODUCES DRAMATIC WEIGHT INCREASE:
BASELINE MISSION NOT REALIZED**



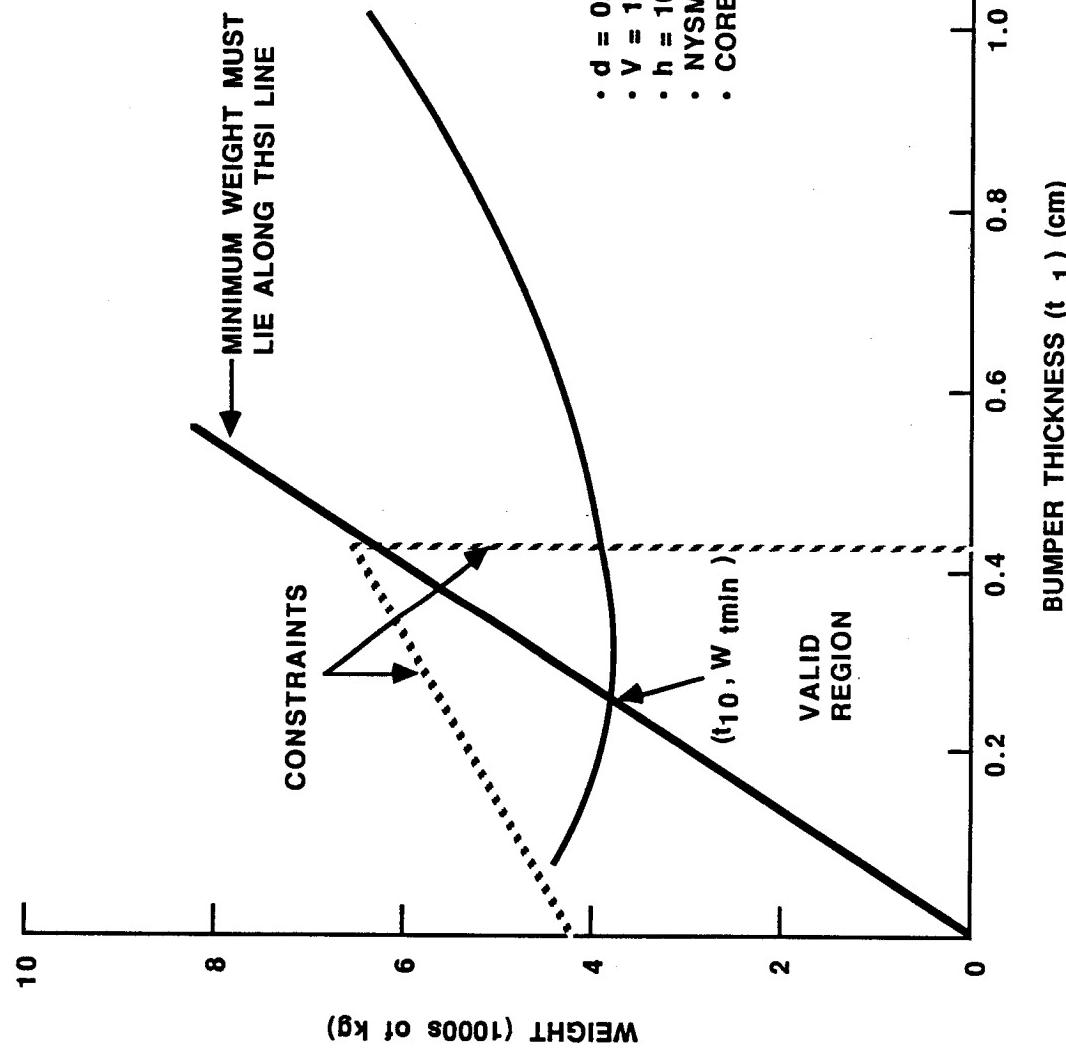
GP METHOD CONFIRMS THE MINIMUM WEIGHT

SHOWN IS THE BASIC OPTIMIZATION PROBLEM SOLVED USING GEOMETRIC PROGRAMMING (GP). THE INTERSECTION OF THE SOLID LINE AND CURVE OCCURS AT THE GLOBAL MINIMUM, VERIFYING THE GP METHODOLOGY.

BM32-91



GP METHOD CONFIRMS THE MINIMUM WEIGHT



SAC-745
10/12/87



OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

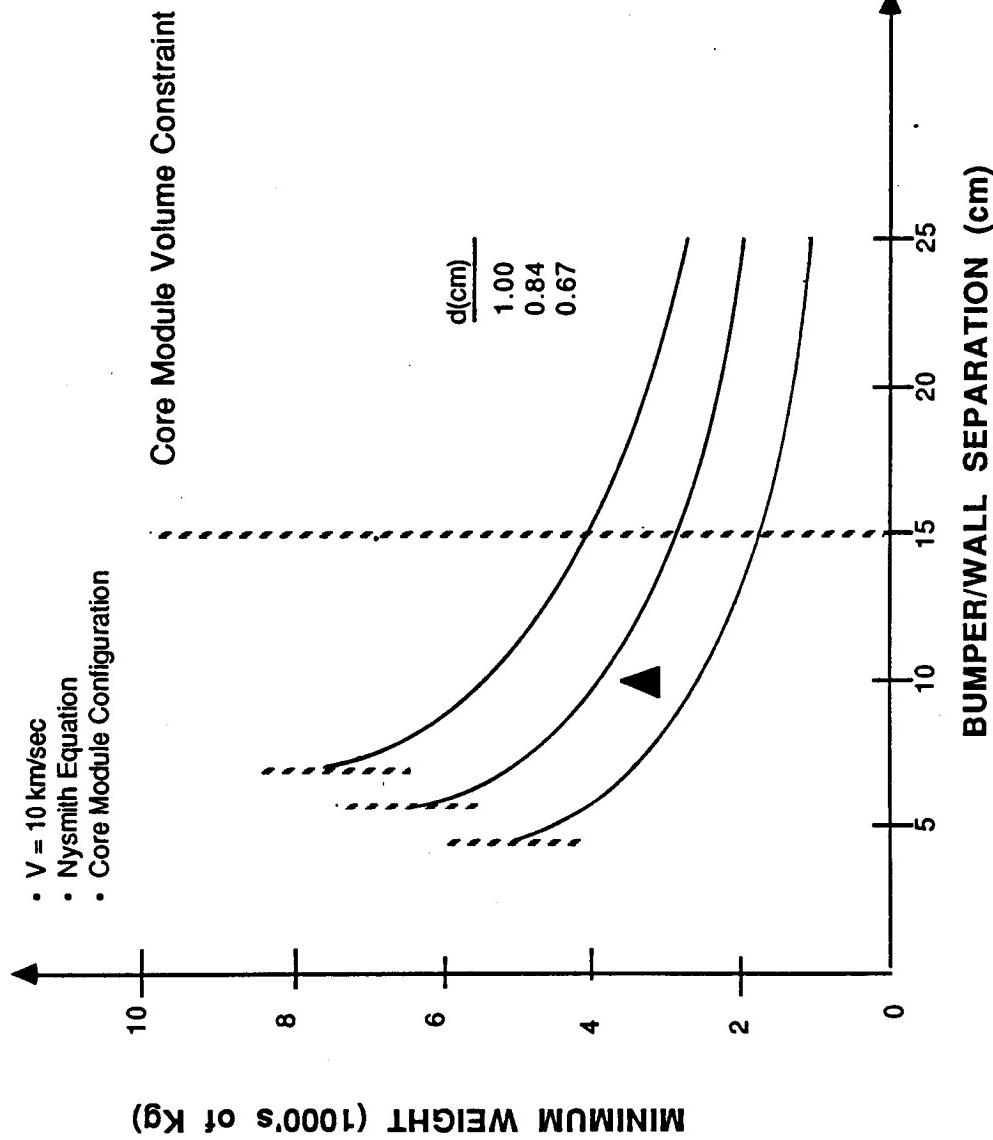
THIS SET OF CURVES SHOWS THE EFFECT OF BUMPER/WALL SEPARATION ON OPTIMAL DESIGN FOR THE NYSMITH PREDICTOR. NOTE THE HIGH PAYOFF FOR INCREASING THIS SEPARATION UP TO ABOUT 15CM, WHICH, INCIDENTALLY, CORRESPONDS TO THE CORE MODULE VOLUME CONSTRAINT FOR SHUTTLE PAYLOADS. FINALLY, TOWARDS THE LEFT OF THE THREE CURVES LIE THE CONSTRAINTS IMPOSED ON THIS SEPARATION BY THE THIRD INEQUALITY CONSTRAINT OF THE NYSMITH EQUATION. NOTE THAT THESE POINTS LIE ON A STRAIGHT LINE THROUGH THE ORIGIN.

BM33-91



OPTIMAL DESIGN IS SENSITIVE TO BUMPER/WALL SEPARATION

- $V = 10 \text{ km/sec}$
- Nyström Equation
- Core Module Configuration



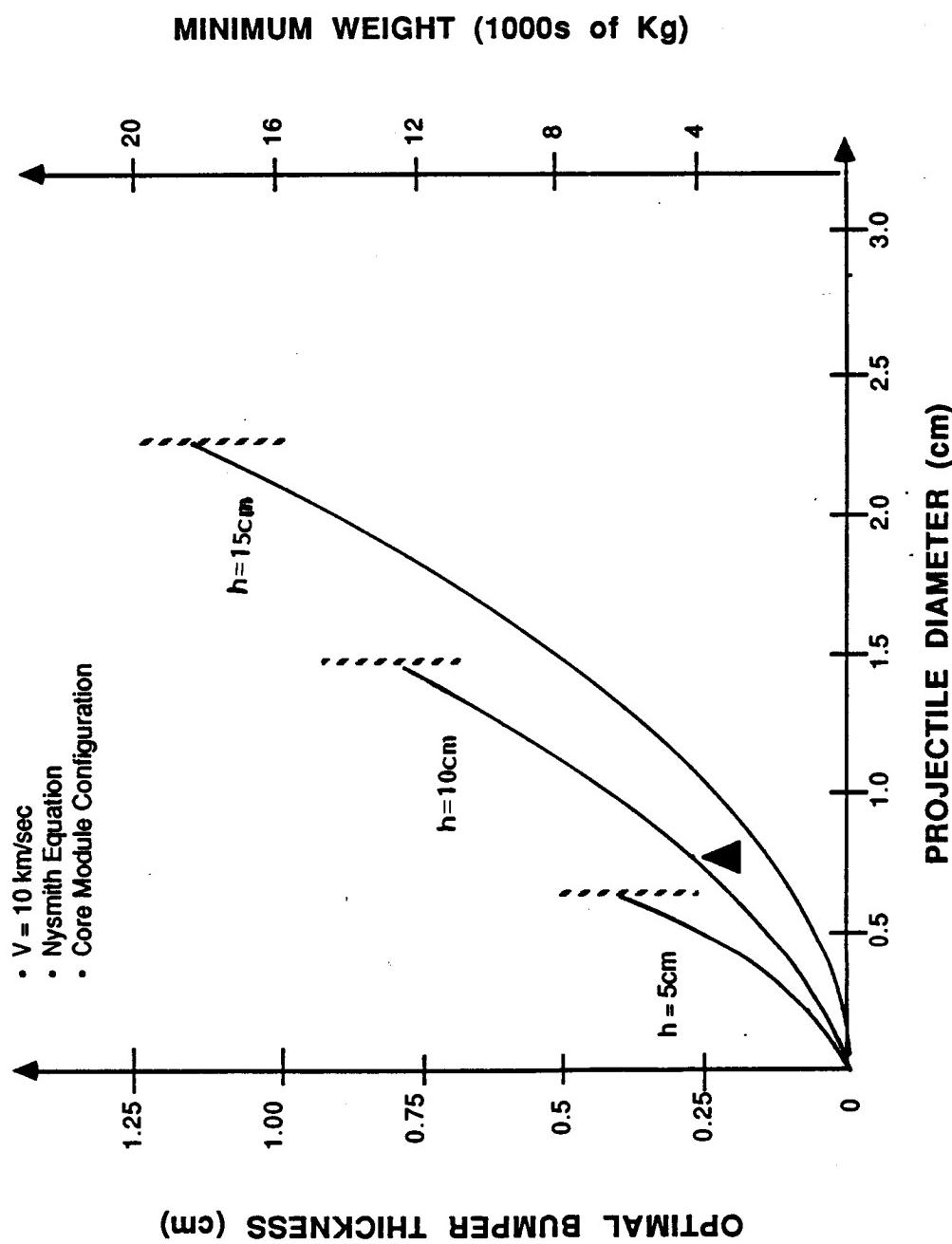
GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN

THE EFFECT OF PROJECTILE DIAMETER ON OPTIMAL BUMPER THICKNESS IS SHOWN. A 20% INCREASE IN DIAMETER ABOVE THE BASELINE REQUIRES A 40% INCREASE IN OPTIMAL BUMPER THICKNESS.

BM34-9/1



GP PROVIDES EFFECT OF THREAT ON OPTIMAL DESIGN



SAU

**OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE
VELOCITY IN HIGH VELOCITY REGIONS**

THE NEXT THREE TRADE SETS SHOW THE EFFECT OF PROJECTILE VELOCITY ON DESIGN FOR VARIOUS PROJECTILE DIAMETERS, FOR 5, 10, AND 15 CM BUMPER/WALL SEPARATIONS. IN THE HIGHER VELOCITY (5-16 KM/SEC) PORTIONS OF THESE CURVES, THE DESIGN REMAINS RELATIVELY INSENSITIVE TO PROJECTILE VELOCITY.

BM24-91

SAC

**OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE
VELOCITY IN HIGH VELOCITY REGIONS**

- $h = 5\text{cm}$
- Nysmith Equation
- Core Module Configuration

MINIMUM WEIGHT (1000s OF kg)

10

8

6

4

2

0

PROJECTILE VELOCITY (km/sec)

16

14

12

10

8

6

4

2

0

PROJECTILE VELOCITY (km/sec)

16

14

12

10

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PROJECTILE VELOCITY (km/sec)

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PROJECTILE VELOCITY (km/sec)

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PROJECTILE VELOCITY (km/sec)

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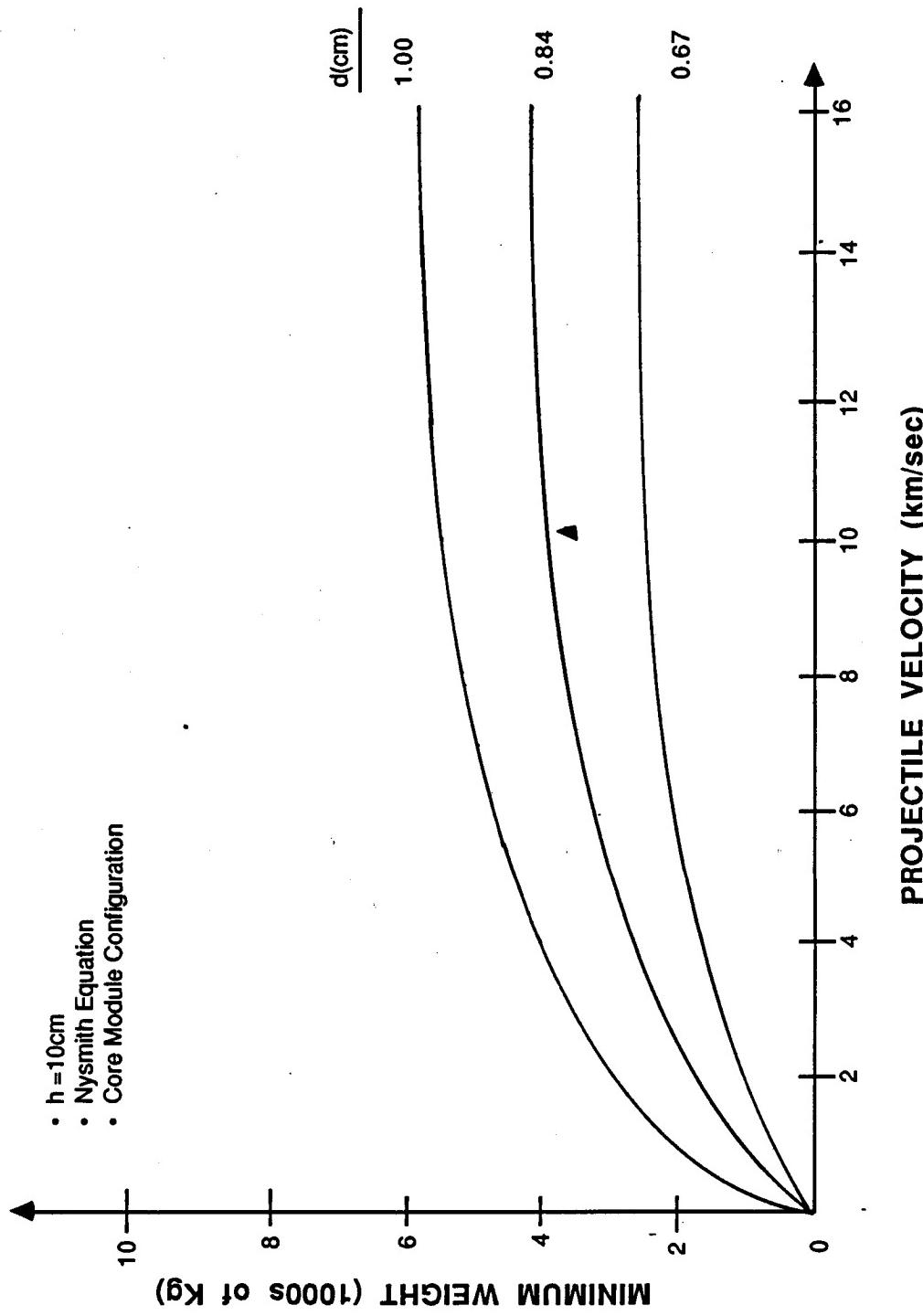
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**OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE
VELOCITY IN HIGH VELOCITY REGIONS**

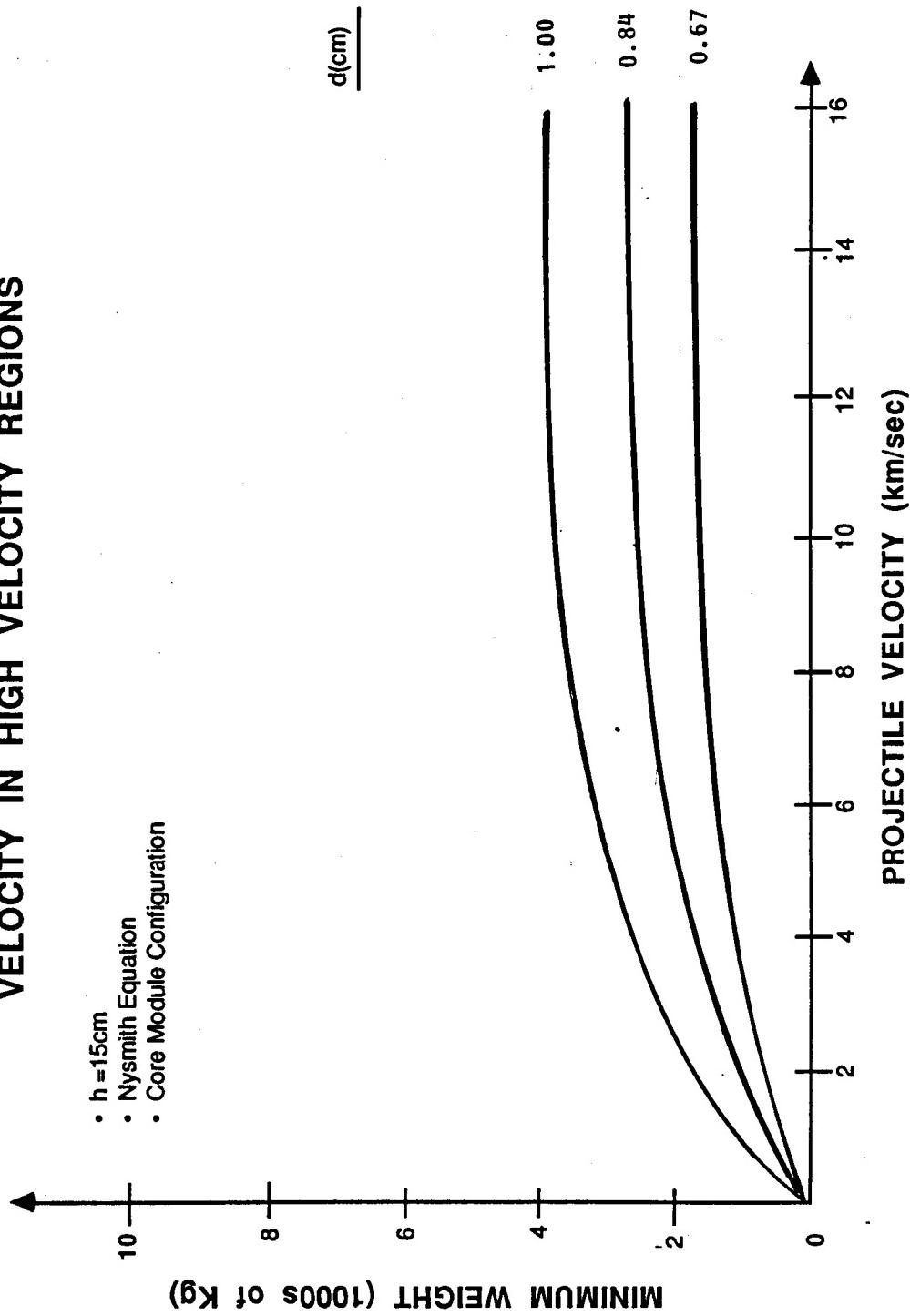


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**OPTIMAL DESIGN IS NOT SENSITIVE TO PROJECTILE
VELOCITY IN HIGH VELOCITY REGIONS**



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OPTIMAL DESIGN IS SENSITIVE TO MISSION
RISK FOR P_0 ABOVE 0.97

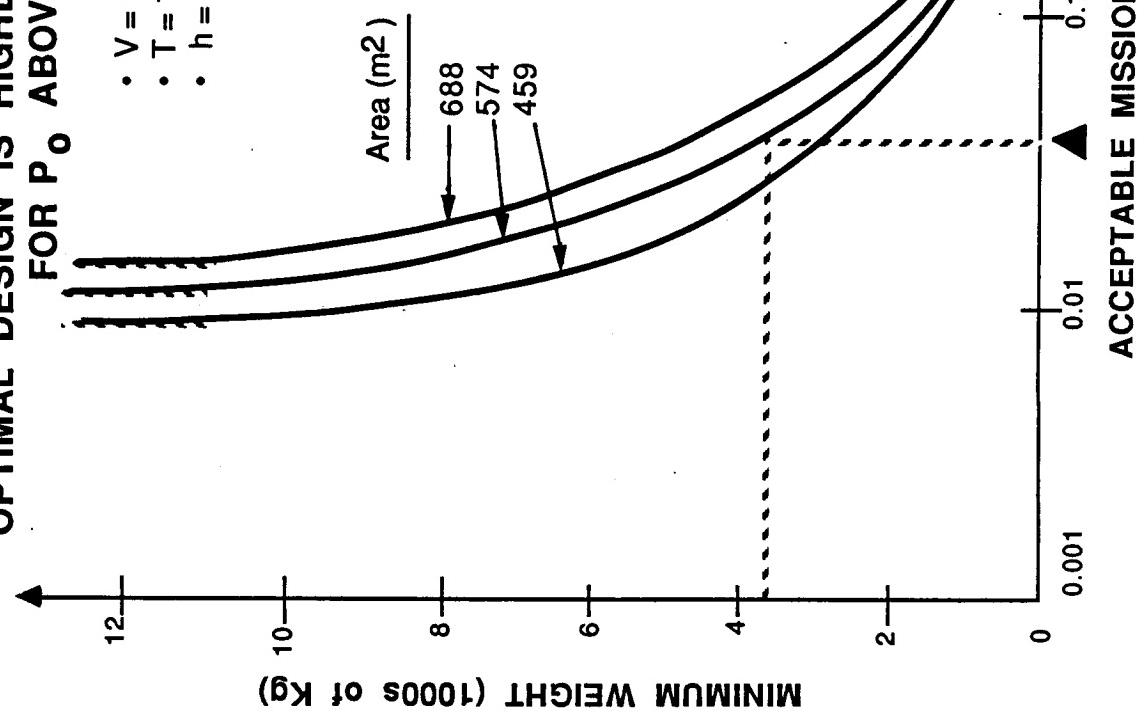
THE EFFECT OF DESIGN ON ACCEPTABLE MISSION RISK FOR VARIOUS
SPACECRAFT DEBRIS AREAS, AND FOR VARIOUS BUMPER/WALL SEPARATIONS
IS SHOWN IN THE NEXT THREE CHARTS. MISSION RISK PLAYS A VERY IMPORTANT
ROLE IN DETERMINING THE OPTIMAL DESIGN.

C - 2
BM36-91



**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK
FOR P_0 ABOVE 0.97**

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ yrs}$
- $h = 10 \text{ cm}$
- Nysmith Equation
- Core Module Configuration



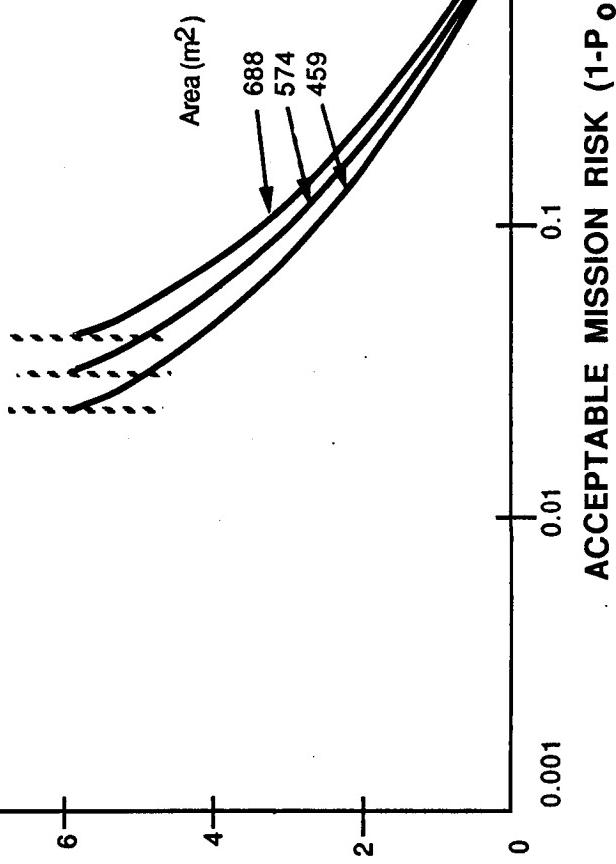
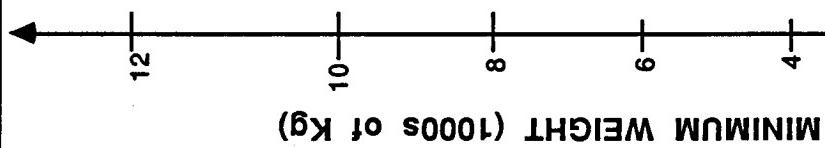
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OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK FOR P_o ABOVE 0.97

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ yrs}$
- $h = 5 \text{ cm}$
- Nysmith Equation
- Core Module Configuration

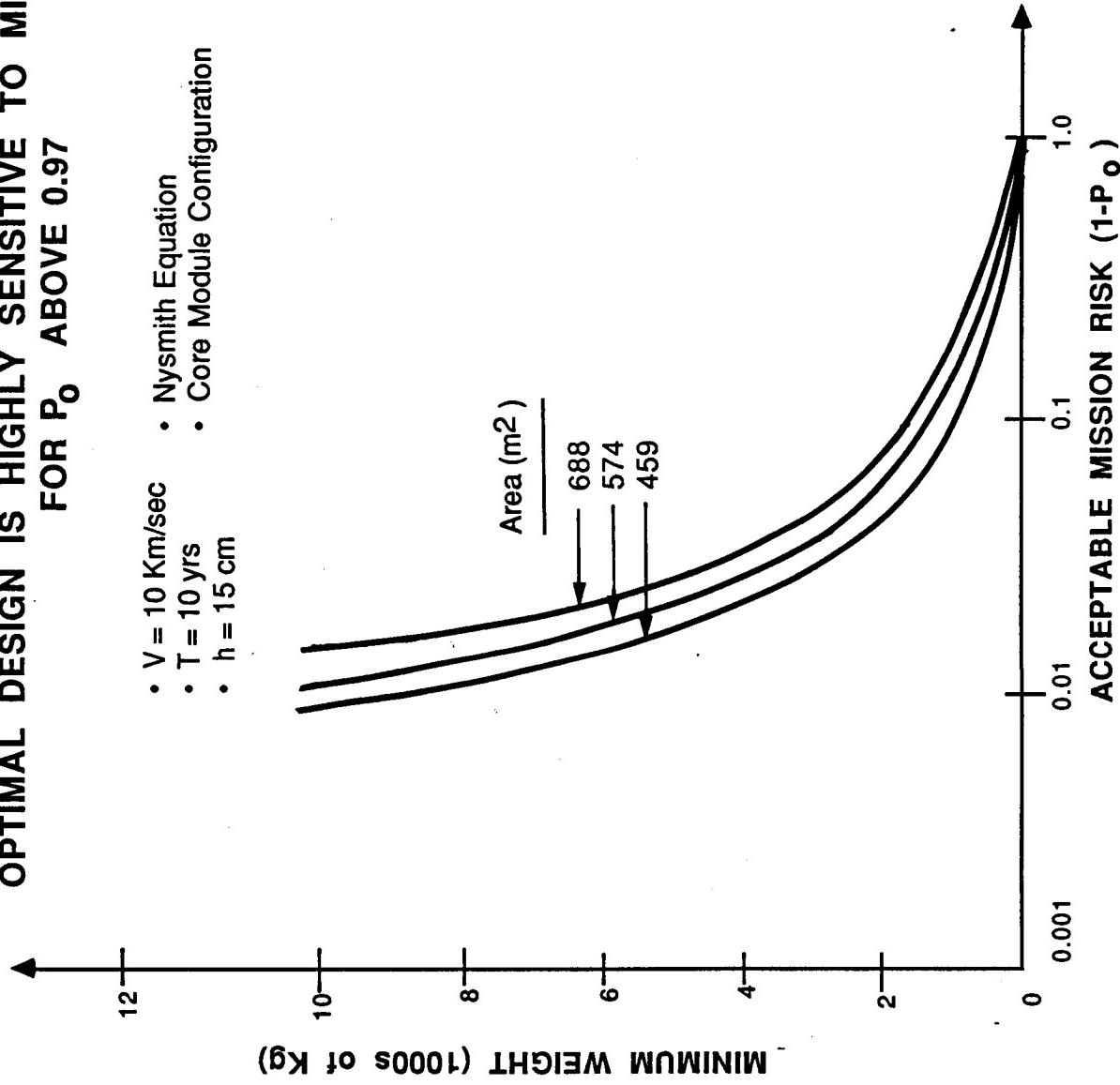


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**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION RISK
FOR P_0 ABOVE 0.97**

- $V = 10 \text{ Km/sec}$
- $T = 10 \text{ yrs}$
- $h = 15 \text{ cm}$
- Nysmith Equation
- Core Module Configuration



**OPTIMAL DESIGN IS SENSITIVE TO MISSION
DURATION IN 10-30 YEAR REGION**

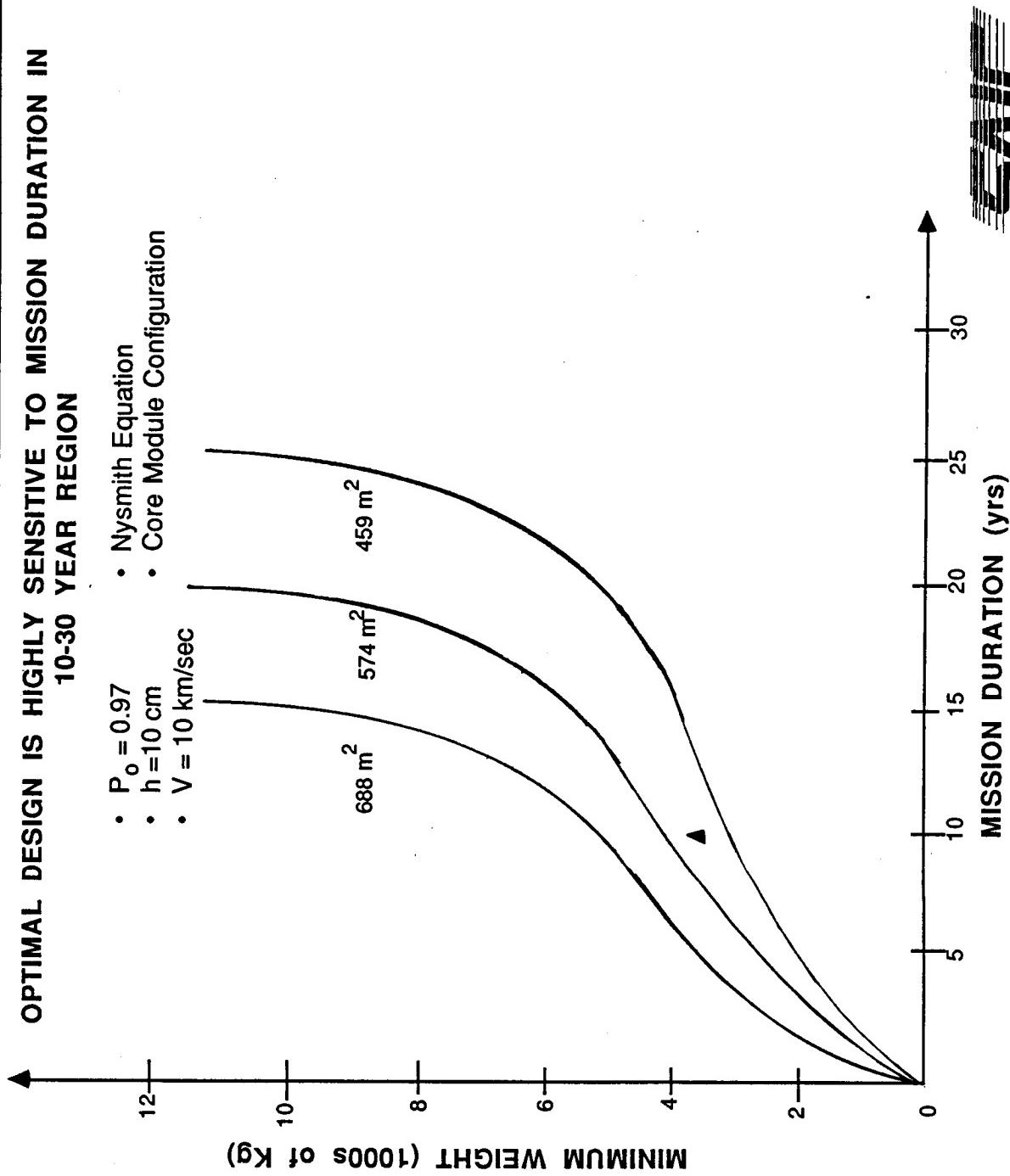
THE NEXT TWO SETS OF TRADES SHOW, FOR DIFFERENT P_0 's, THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR VARIOUS SPACECRAFT DEBRIS AREAS. NOTE THE HIGH SENSITIVITY, EVEN INFLECTION IN SOME CASES, OCCURRING IN THE 10-30 YEAR RANGE.

BM37-9/1



**OPTIMAL DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION IN
10-30 YEAR REGION**

- $P_o = 0.97$
- $h = 10 \text{ cm}$
- $V = 10 \text{ km/sec}$
- Nysmith Equation
- Core Module Configuration

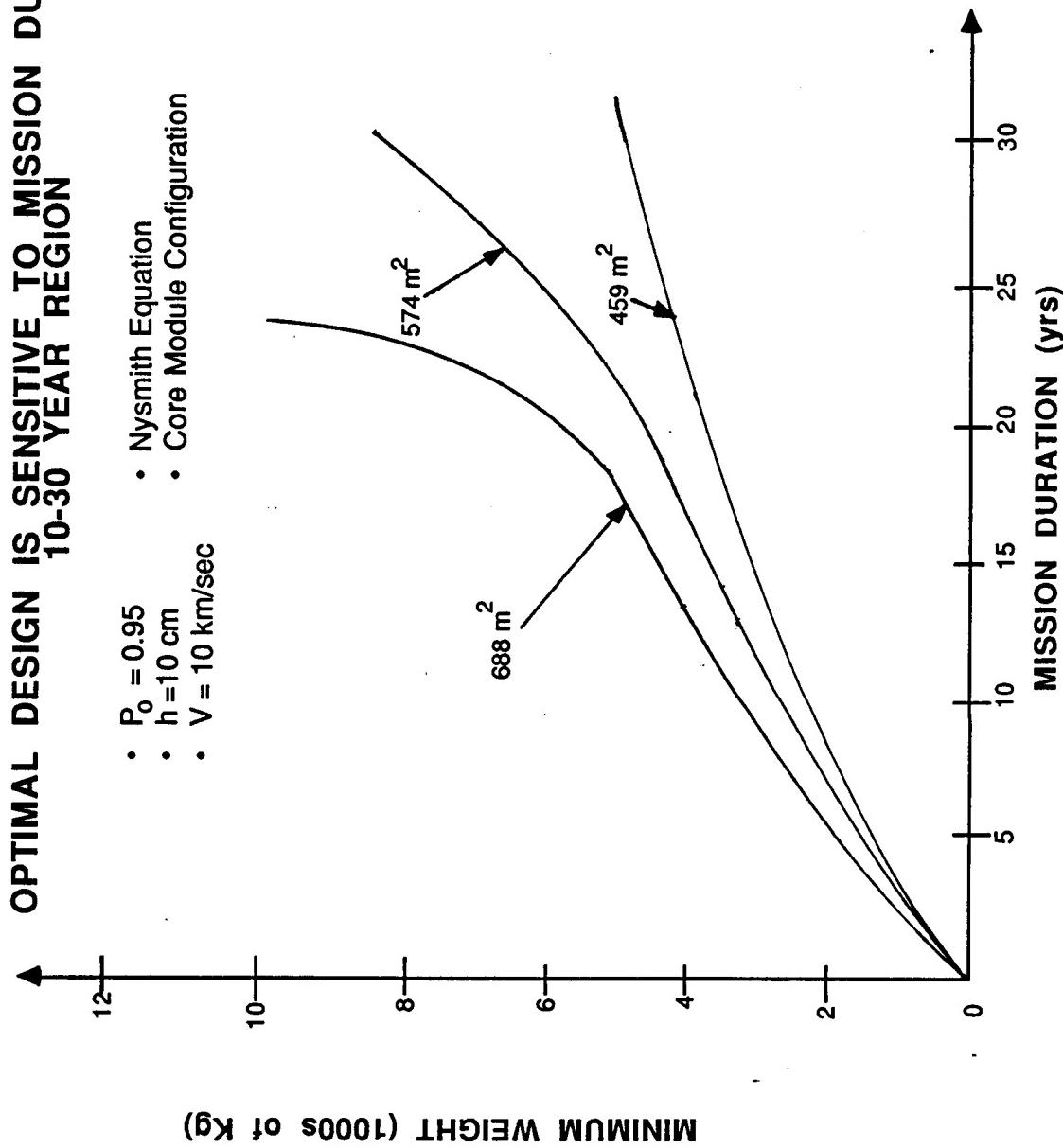


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SALE™

**OPTIMAL DESIGN IS SENSITIVE TO MISSION DURATION IN
10-30 YEAR REGION**

- $P_0 = 0.95$
- $h = 10 \text{ cm}$
- $V = 10 \text{ km/sec}$
- Nysmith Equation
- Core Module Configuration



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SECTION IV

**GEOMETRIC PROGRAMMING APPLIED TO
THE BOEING SUBPREDICTORS.**

BM29-8/21



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WHAT YOU WILL SEE IN SECTION IV

- DEFINITIONS AND BASELINE DESIGN PARAMETERS FOR THE THREE BOEING SUBPREDICTORS
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING SUBPREDICTORS
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
 - PROJECTILE VELOCITY
 - BUMPER/WALL SEPARATION
 - PROJECTILE DIAMETER
 - MISSION RISK
 - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER

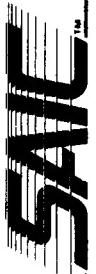
BM4 10/13



THE PEN4 PREDICTOR

THE PEN4 PREDICTOR WITH PARAMETER DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THERE IS NO DEPENDENCE ON BUMPER/WALL SEPARATION. ALSO, NOTE THAT THE PEN4 PREDICTOR IS VELOCITY CONSTRAINED. THIS PREDICTOR WAS OPTIMIZED USING A SEARCH TECHNIQUE, WITH THE VELOCITY CONSTRAINT CHECKED EXTERNALLY TO THE OPTIMIZATION.

BM15-8/21



THE PEN4 PREDICTOR

$$t_2 = 1.67 \left(\frac{C_1 \rho_p}{2 S y_2} \right)^{.31} \left(\frac{.281 D \rho_p}{\rho_2^2} \right)^{1/3} \cos(\theta)$$

$$C_1 = \frac{a-b}{c+d}$$

$$a = 1.33 V^2 R_p^2 \rho_p$$

$$b = 8 S y_1 t_1 e^{-3.125 \times 10^{-4} V / \cos(\theta)}$$

$$c = 1.33 R_p^2 \rho_p$$

$$d = R_p t_1 \rho_1 / \cos(\theta)$$

Valid for $V \leq V_f + 4000$, where

$$V_f = \begin{cases} 4100, & \text{if } t_1 / D \leq 0.4 \\ 4986 (t_1 / D)^{0.21}, & \text{if } t_1 / D > 0.4 \end{cases}$$

BMO1-8/21



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THE PEN4 PREDICTOR (CONTINUED)

- V = particle velocity, ft/sec
- t_1 = bumper thickness, ft
- t_2 = wall thickness, ft
- D = particle diameter, ft
- R_p = particle radius, ft
- ρ_p = projectile density, slugs/ft³
- ρ_1 = bumper density, slugs/ft³
- ρ_2 = wall density, slugs/ft³
- θ = impact angle from the normal, degrees
- Sy_1 = bumper yield strength, lb/ft²
- Sy_2 = wall yield strength, lb/ft²

No bumper/wall separation dependency



BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE PEN4 PREDICTOR ARE SHOWN. SINCE THIS PREDICTOR IS NOT VALID FOR A PROJECTILE VELOCITY OF 10 KM/SEC, NO OPTIMAL DESIGN IS INDUCED.

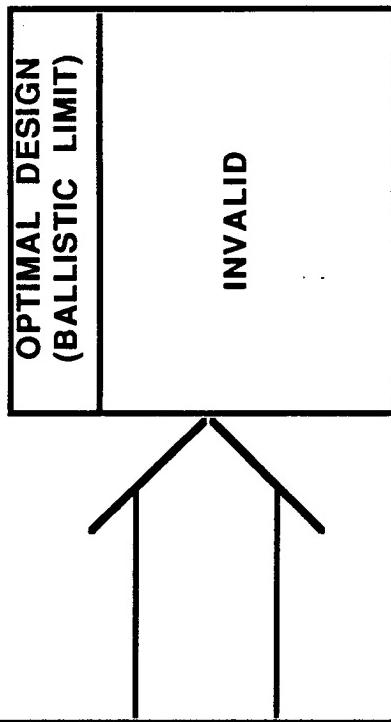
BM02-99



BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS

$P_0 = 0.97$	(PROBABILITY OF NO PENETRATION)
$T = 10 \text{ yrs}$	(MISSION DURATION)
$A_d = 574 \text{ m}^2$	(DEBRIS AREA)
$A_m = 403 \text{ m}^2$	(METEOROID AREA)
$Alt = 500 \text{ km}$	(AVERAGE ALTITUDE)
$v_m = 20 \text{ km/sec}$	(AVERAGE METEOROID VELOCITY)
$v_d = 10 \text{ km/sec}$	(AVERAGE DEBRIS VELOCITY)
$\rho_m = 0.5 \text{ gm/cm}^3$	(METEOROID DENSITY)
$\rho_d = 2.81 \text{ gm/cm}^3$	(DEBRIS DENSITY)
$\rho_1 = 2.81 \text{ gm/cm}^3$	
$\rho_2 = 2.81 \text{ gm/cm}^3$	
$\theta = 0 \text{ degrees}$	
$Sy_1 = 7344000 \text{ lb/ft}^2$	(51 Ksi)
$Sy_2 = Sy_1$	



BM03-8/21

THE BURCH PREDICTOR (NORMAL IMPACT)

THE BURCH PREDICTOR FOR NORMAL IMPACTS IS SHOWN WITH PARAMETER DEFINITION. NOTE THAT THERE IS NO DEPENDENCE ON PROJECTILE OR WALL MATERIAL PROPERTIES.

BM16-8/21

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THE BURCH PREDICTOR (NORMAL IMPACT)

$$t_2 = \left(\frac{F_1 D}{N} \right)^{1.71} \left(\frac{C}{V} \right)^{2.29} / S^{0.71}, \text{ where}$$

$$F_1 = 2.42 (t_1/D)^{-0.33} + 4.26 (t_1/D)^{0.33} - 4.18$$

C = speed of sound in shield, ft/sec = $\sqrt{E_1 / \rho_1}$
 E₁ = Youngs Modulus of Elasticity for bumper, lb/ft^{-sec}²
 ρ_1 = bumper density, lb/ft³

V = projectile velocity, ft/sec
 S = spacing, inches

D = projectile diameter, inches
 t₁ = bumper thickness, inches

t₂ = wall thickness, inches
 N = number of plates to penetrate after 1st bumper

No projectile material property dependency
 No wall material property dependency



THE MODIFIED BURCH PREDICTOR

THE MODIFIED BURCH PREDICTOR IS SHOWN FOR REFERENCE. NOTE THAT THIS PREDICTOR IS A POSYNOMIAL, WHICH ALLOWS IT TO BE OPTIMIZED GLOBALLY USING GEOMETRIC PROGRAMMING.

BM17-8/21



THE MODIFIED BURCH PREDICTOR

SAME AS THE BURCH PREDICTOR EXCEPT:

$$F_1 = 2.8 (t_1/D)^{0.57} + 1.58 (t_1/D)^{-0.57}$$

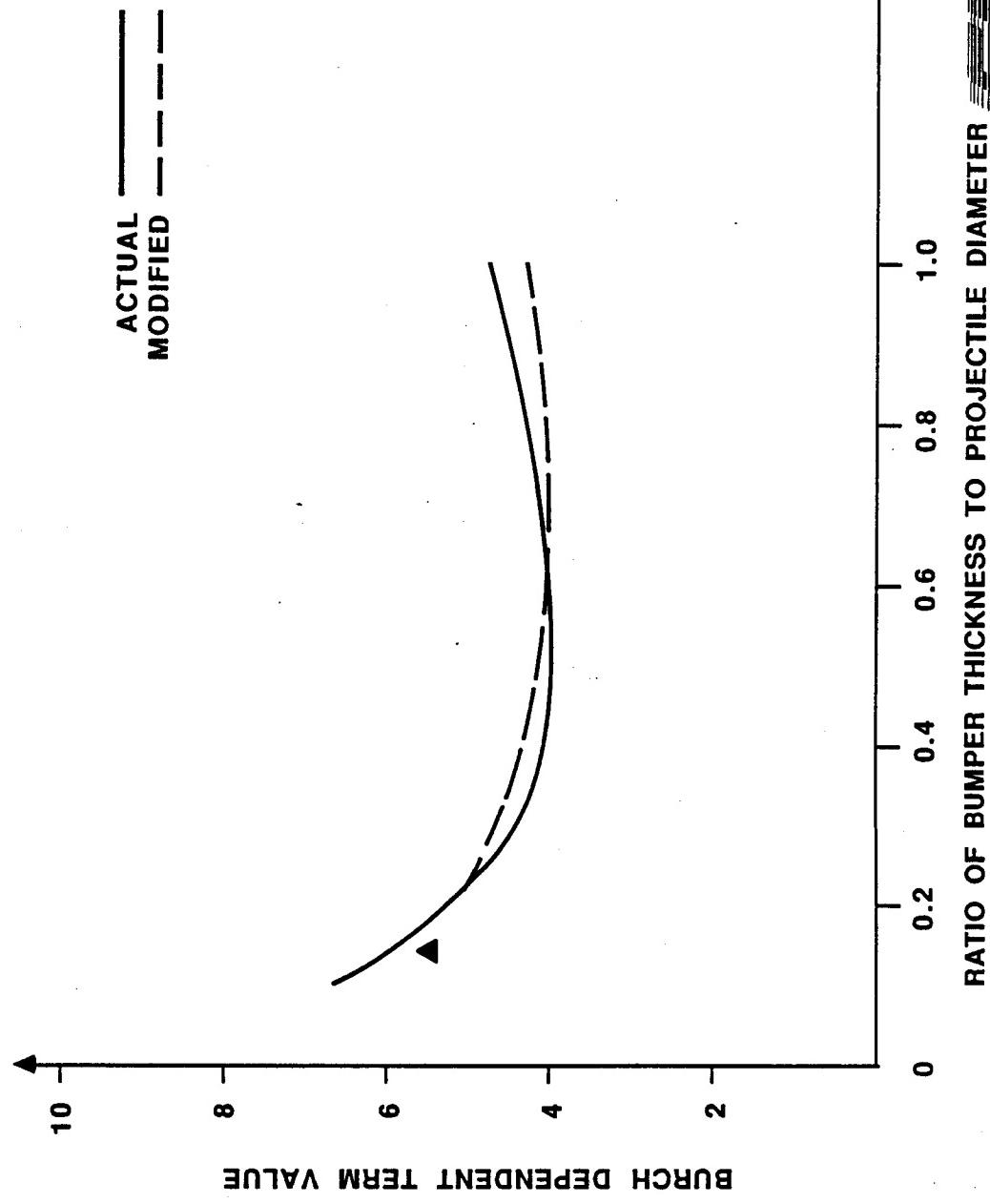
BM10-8/21

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MODIFIED BURCH PREDICTOR INDUCES SMALL ERRORS

SHOWN IS THE BURCH DEPENDENT TERM VALUE (PROPORTIONAL TO THE WALL THICKNESS) AS A FUNCTION OF THE RATIO OF THE BUMPER THICKNESS TO PROJECTILE DIAMETER FOR THE BURCH AND MODIFIED BURCH PREDICTORS. USING THE MODIFIED BURCH PREDICTOR ALLOWS THE DESIGNER TO APPLY THE GEOMETRIC PROGRAMMING OPTIMIZATION TECHNIQUE, THUS REDUCING COMPUTER USAGE AND GUARANTEEING GLOBAL DESIGN OPTIMIZATION, ALL FOR A SMALL PRICE IN TERMS OF DESIGN ERROR.

MODIFIED BURCH PREDICTOR INDUCES SMALL ERRORS



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8/4/87

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BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE MODIFIED BURCH PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 26% BUMPER, 74% WALL.

BM03A-99



BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS	
P_0	0.97 (PROBABILITY OF NO PENETRATION)
T	10 yrs (MISSION DURATION)
A_d	574 m ² (DEBRIS AREA)
A_m	403 m ² (METEOROID AREA)
Alt	500 km (AVERAGE ALTITUDE)
v_m	20 km/sec (AVERAGE METEOROID VELOCITY)
v_D	10 km/sec (AVERAGE DEBRIS VELOCITY)
ρ_m	0.5 gm/cm ³ (METEOROID DENSITY)
ρ_D	2.81 gm/cm ³ (DEBRIS DENSITY)
S	10 cm (BUMPER/WALL SEPARATION)
E_1	7.239×10^{11} gm/cm ² ρ_1 = 2.81 gm/cm ³

OPTIMAL DESIGN (BALLISTIC LIMIT)	
BUMPER	$t_{10} = 0.09\text{cm}$ (0.04 in)
WALL	$t_{20} = 0.25\text{cm}$ (0.10 in)

BM04-8/21



THE WILKINSON PREDICTOR

THE WILKINSON PREDICTOR WITH PARAMETER DEFINITION IS SHOWN FOR REFERENCE. NOTE THAT THIS PREDICTOR FORMS A COMPLETE SET OF PARAMETERS. ALSO, NOTE THAT THE WILKINSON PREDICTOR IS A PIECEWISE CONTINUOUS MODEL. THE WILKINSON PREDICTOR WAS OPTIMIZED USING GEOMETRIC PROGRAMMING.

THE WILKINSON PREDICTOR

$$t_2 = 0.364 D^4 \rho_p^2 v_n / (L_2 S^2 \rho_1 t_1 \rho_2), \text{ if } \frac{D \rho_p}{\rho_1 t_1} > 1.$$

$$t_2 = 0.364 D^3 \rho_p v_n / (L_2 S^2 \rho_2), \text{ if } \frac{D \rho_p}{\rho_1 t_1} \leq 1.$$

ρ_p = projectile density, gm/cm³

D = projectile diameter, cm

v_n = normal component of velocity vector, km/sec

S = spacing, cm

ρ_1 = bumper density, gm/cm³

ρ_2 = wall density, gm/cm³

L₂ = wall material constant

t₁ = bumper thickness, cm

t₂ = wall thickness, cm

BASELINE DESIGN PARAMETERS

**THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE WILKINSON
PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRI-
BUTION IS 50% WALL, 50% BUMPER.**

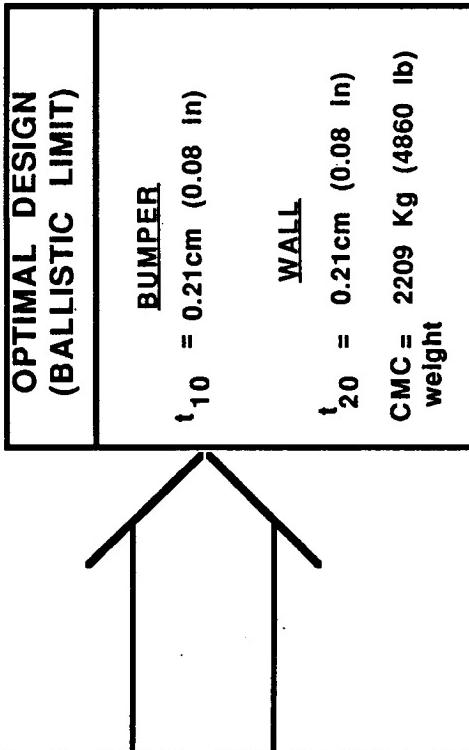
BM01-99



BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS

$P_0 = 0.97$	(PROBABILITY OF NO PENETRATION)
$T = 10 \text{ yrs}$	(MISSION DURATION)
$A_d = 574 \text{ m}^2$	(DEBRIS AREA)
$A_m = 403 \text{ m}^2$	(METEOROID AREA)
$\text{Alt} = 500 \text{ km}$	(AVERAGE ALTITUDE)
$v_m = 20 \text{ km/sec}$	(AVERAGE METEOROID VELOCITY)
$v_d = 10 \text{ km/sec}$	(AVERAGE DEBRIS VELOCITY)
$\rho_m = 0.5 \text{ gm/cm}^3$	(METEOROID DENSITY)
$\rho_d = 2.81 \text{ gm/cm}^3$	(DEBRIS DENSITY)
$s = 10 \text{ cm}$	(BUMPER/WALL SEPARATION)
$\rho_1 = 2.81 \text{ gm/cm}^3$	
$\rho_2 = \rho_1$	
$L_2 = 0.401$	



BM05-8/21

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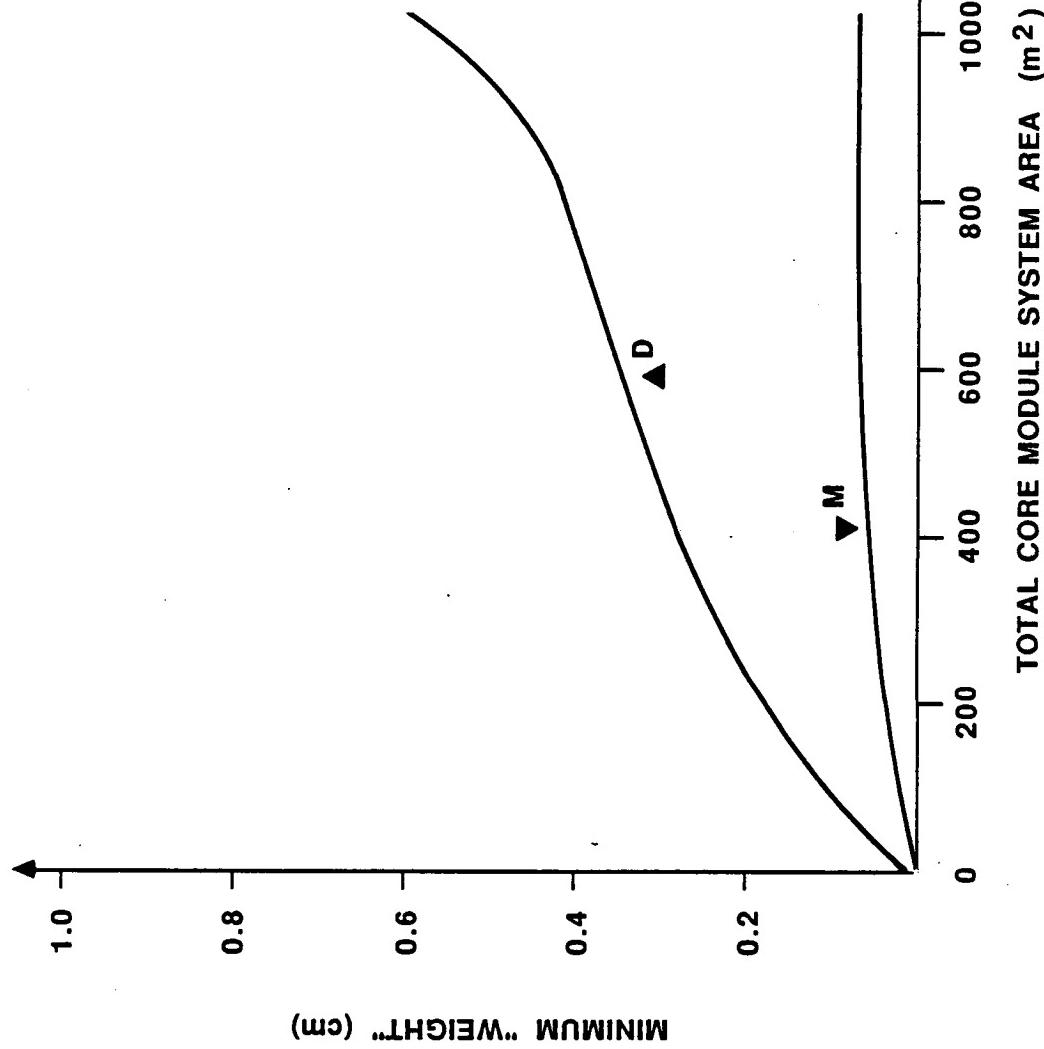
DEBRIS ENVIRONMENT DRIVES FOR MODIFIED BURCH

THE EFFECT OF CHANGES IN THE CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID CASES FOR THE MODIFIED BURCH SUBPREDICTOR IS SHOWN. AGAIN, THE DEBRIS ENVIRONMENT DOMINATES THAT OF THE METEOROID.

BM04-8/5

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DEBRIS ENVIRONMENT DRIVES FOR MODIFIED BURCH



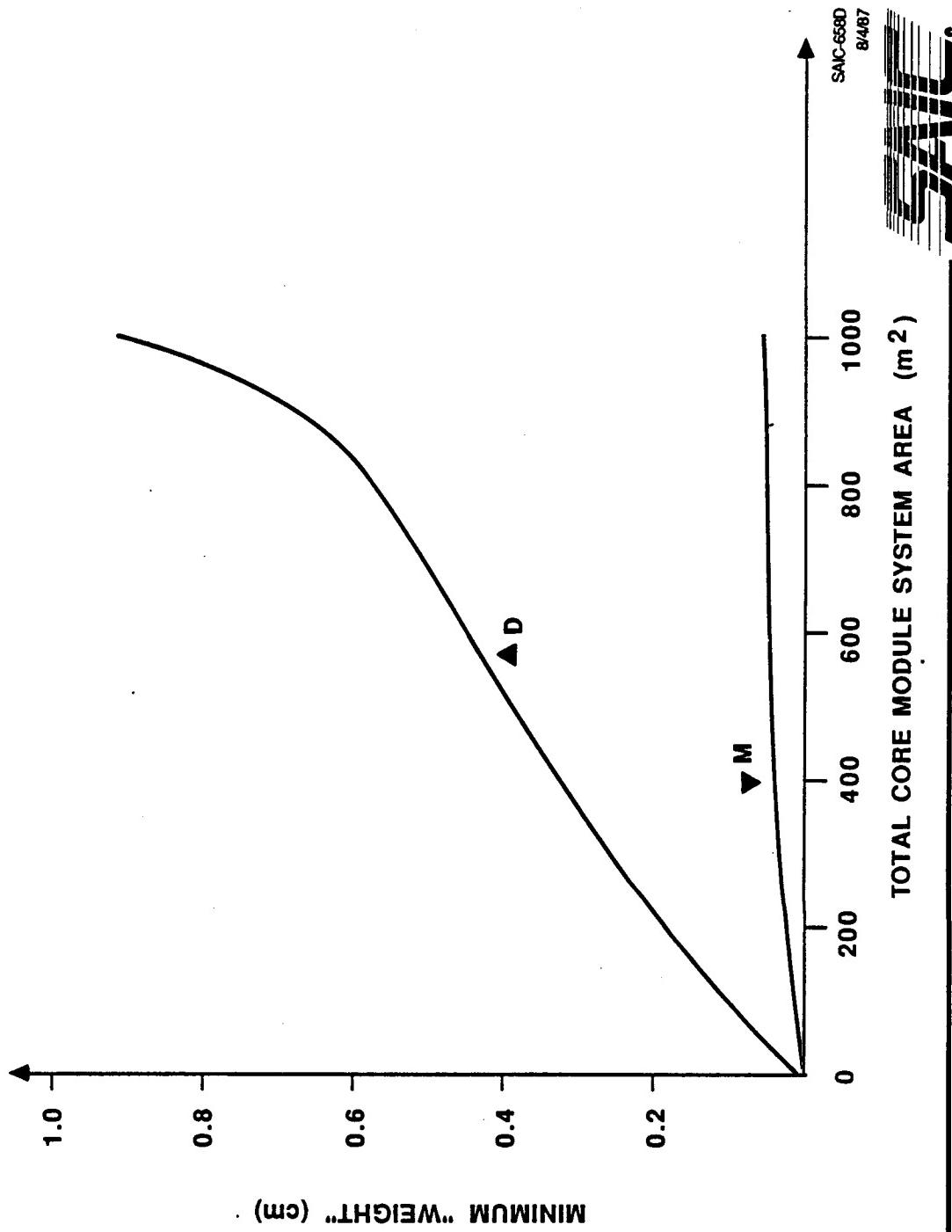
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DEBRIS ENVIRONMENT DRIVES FOR WILKINSON

SHOWN IS THE EFFECT OF CHANGES IN CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE WILKINSON SUBPREDICTOR. THE DOMINANCE OF THE DEBRIS SCENARIO OVER THE METEOROID SCENARIO IS MORE STRIKING FOR WILKINSON THAN NYSMITH BECAUSE THE WILKINSON PREDICTOR ACCOUNTS FOR PROJECTILE DENSITY AND THE NYSMITH DOES NOT.

DEBRIS ENVIRONMENT DRIVES FOR WILKINSON



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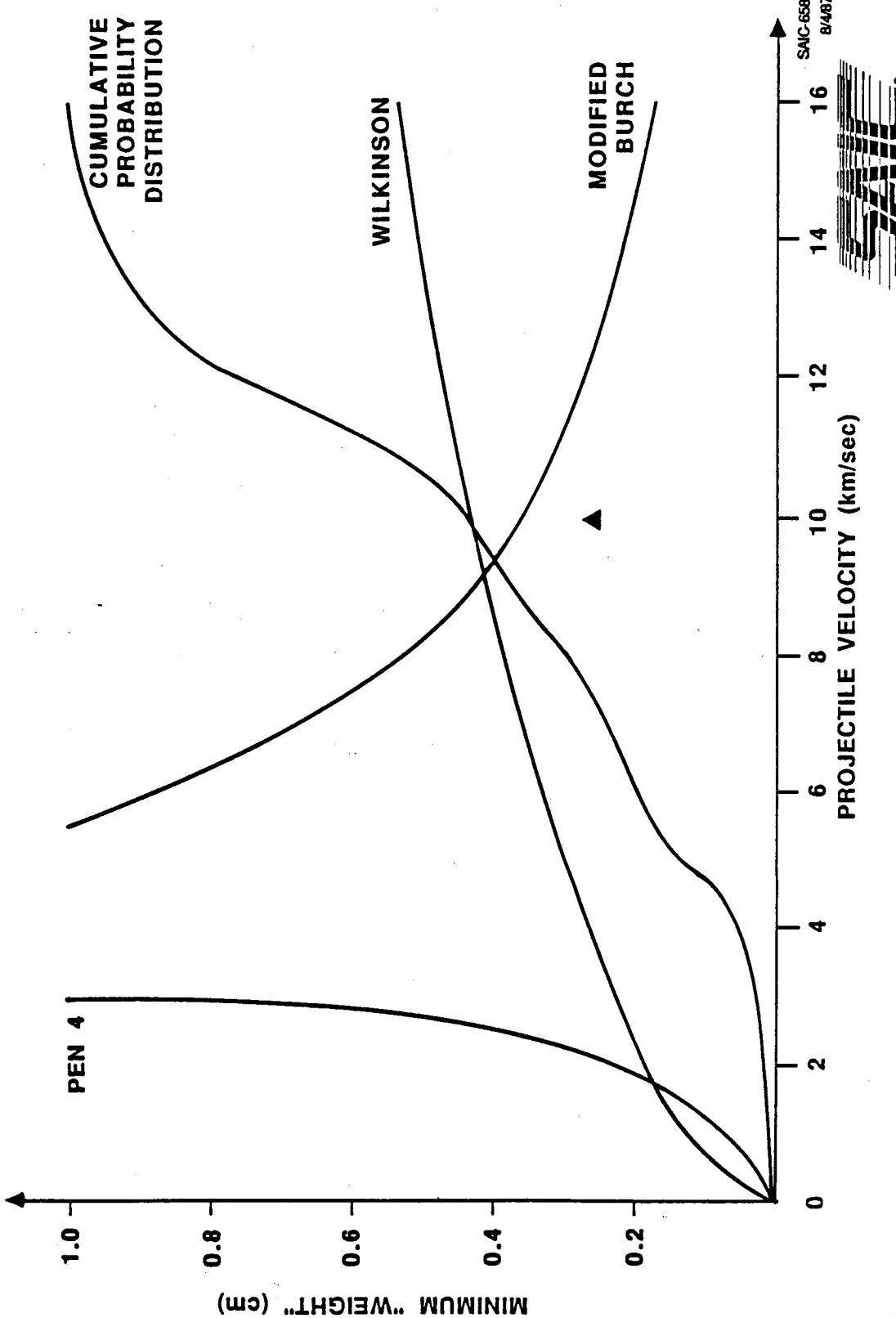
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TOTAL CORE MODULE SYSTEM AREA (m²)

VELOCITY SENSITIVITY FOR THE BOEING SUBPREDICTORS

THE DESIGN SENSITIVITY TO PROJECTILE VELOCITY FOR THE THREE BOEING SUBPREDICTORS IS SHOWN. BOTH THE PEN4 AND WILKINSON SUBPREDICTORS SHOW OPTIMAL DESIGN INCREASING WITH INCREASING VELOCITY, ALTHOUGH THE PEN4 CURVE IS CONVEX, WHILE THE WILKINSON CURVE IS CONCAVE. FURTHERMORE, THE PEN4 SUBPREDICTOR IS ONLY VALID UP TO ABOUT 2.85 km/sec. THE MODIFIED BURCH SUBPREDICTOR IS A DECREASING CURVE AND INTERSECTS THE WILKINSON CURVE AT ABOUT 9 km/sec. ALSO SHOWN IS THE CUMULATIVE PROBABILITY DISTRIBUTION FOR SPACE DEBRIS AT 500 km ALTITUDE AND 30° INCLINATION. NOTE THAT 80% PROBABILITY OCCURS AT ROUGHLY 12 km/sec. NOTE, ALSO, THAT VELOCITIES UP TO 10 km/sec ONLY ACCOUNT FOR ROUGHLY 40% OF THE THREAT DISTRIBUTION.

VELOCITY SENSITIVITY FOR THE BOEING SUBPREDICTORS



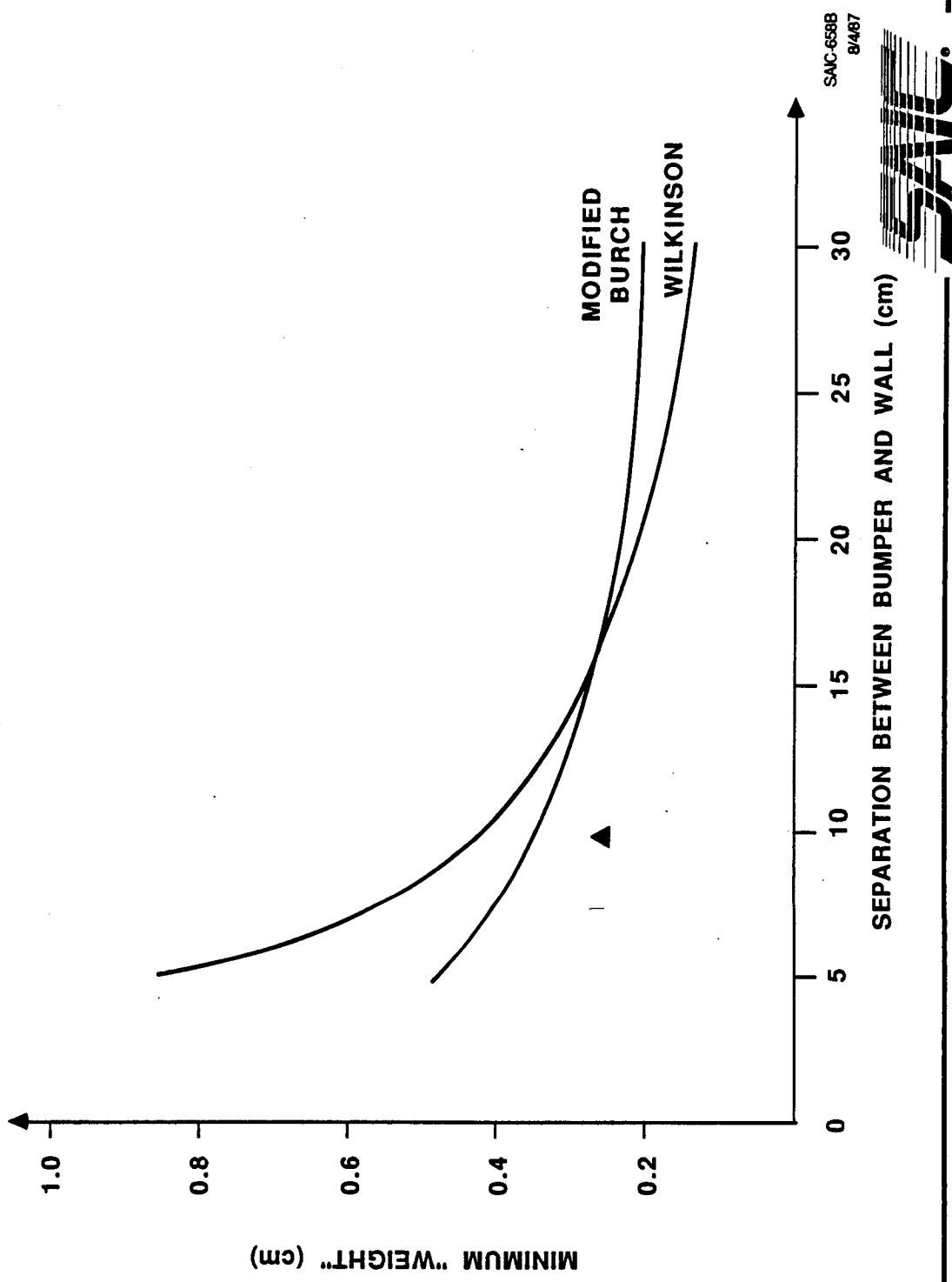
**GP SHOWS SEPARATION SENSITIVITIES
FOR MODIFIED BURCH AND WILKINSON**

THE DECREASE IN OPTIMAL DESIGN FOR AN INCREASE IN BUMPER/WALL SEPARATION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS SHOWN. NOTE THAT THE WILKINSON CURVE IS MUCH MORE SENSITIVE TO INCREASES IN BUMPER/WALL SEPARATION.

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**GP SHOWS SEPARATION SENSITIVITIES FOR
MODIFIED BURCH AND WILKINSON**



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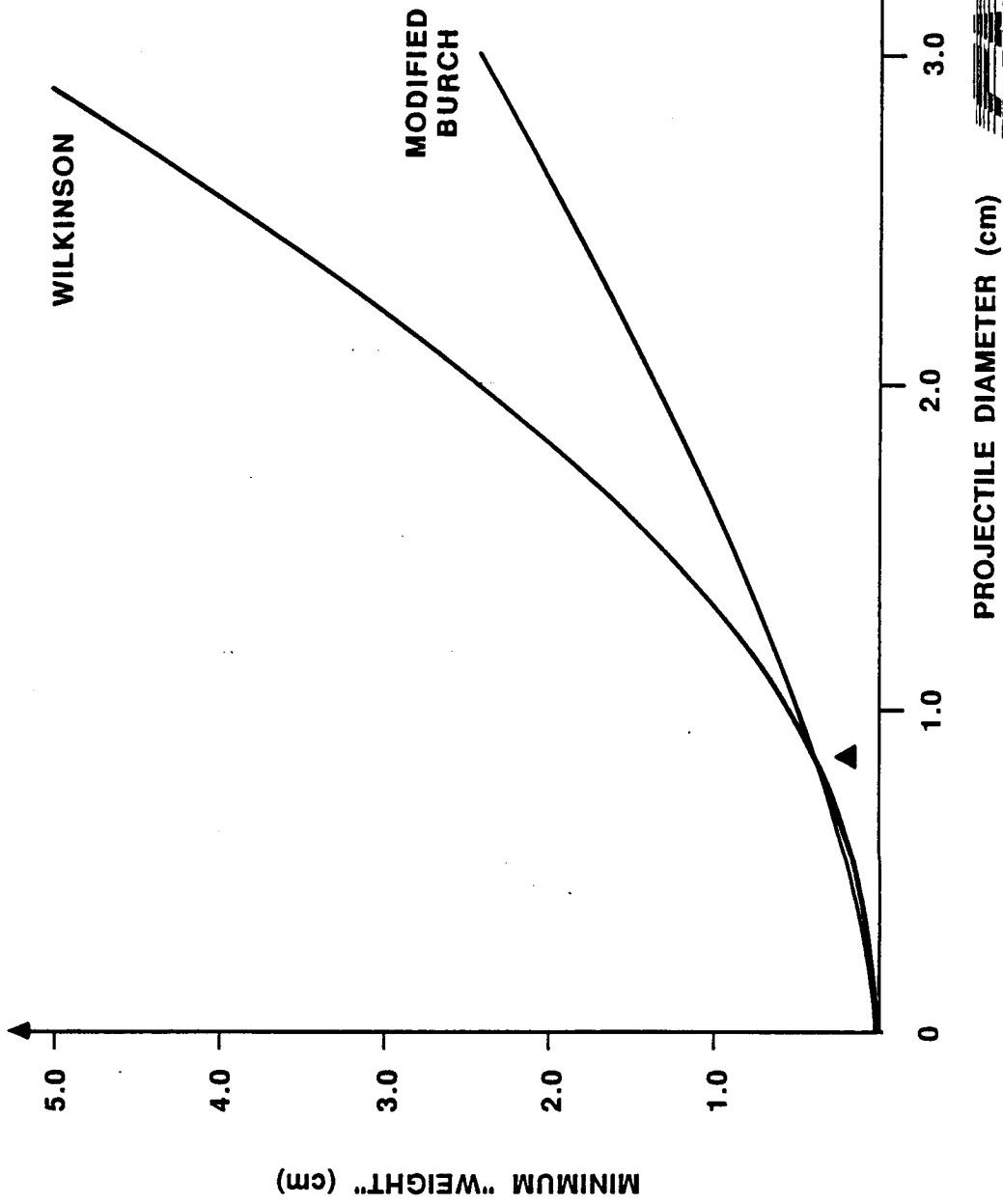
SENSITIVITY OF OPTIMAL DESIGN TO THREAT

SHOWN IN THE NEXT TWO CHARTS IS THE DESIGN SENSITIVITY TO PROJECTILE DIAMETER FOR THE WILKINSON AND MODIFIED BURCH SUBPREDICTORS. NOTE THAT THE MODIFIED BURCH CURVE DOMINATES THE DESIGN UP TO ABOUT 0.52 cm PROJECTILE DIAMETER, WHERE THE WILKINSON CURVE TAKES OVER.

BM05-8/5



SENSITIVITY OF OPTIMAL DESIGN TO THREAT



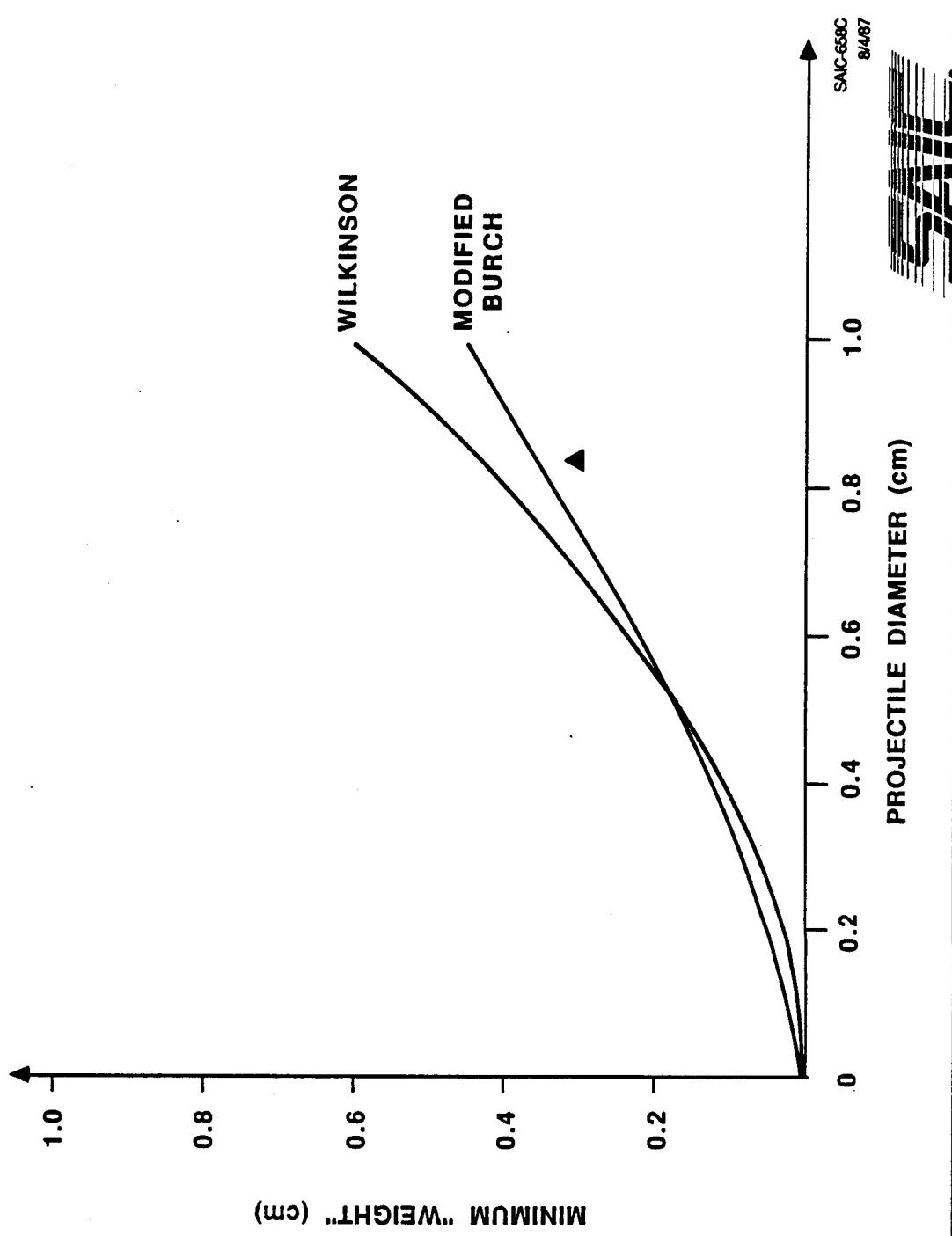
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SENSITIVITY OF OPTIMAL DESIGN TO THREAT



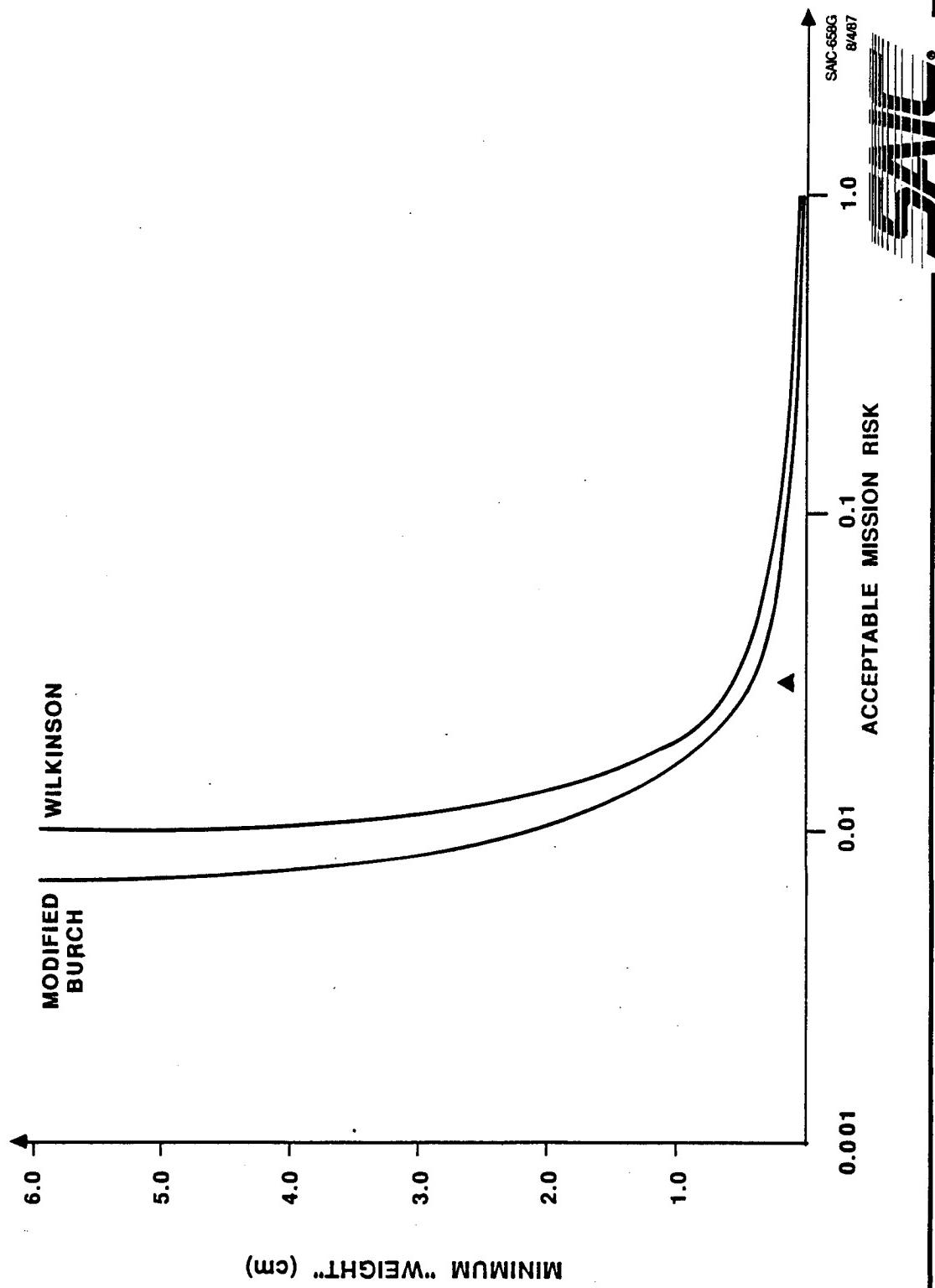
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WILKINSON MORE SENSITIVE TO MISSION RISK THAN MODIFIED BURCH

SHOWN IS THE EFFECT OF INCREASING MISSION RISK (DECREASING PROBABILITY OF NO PENETRATION) ON OPTIMAL DESIGN FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS. NOTE THAT THE WILKINSON CURVE DOMINATES EXCEPT IN THE VERY HIGH MISSION RISK REGION.

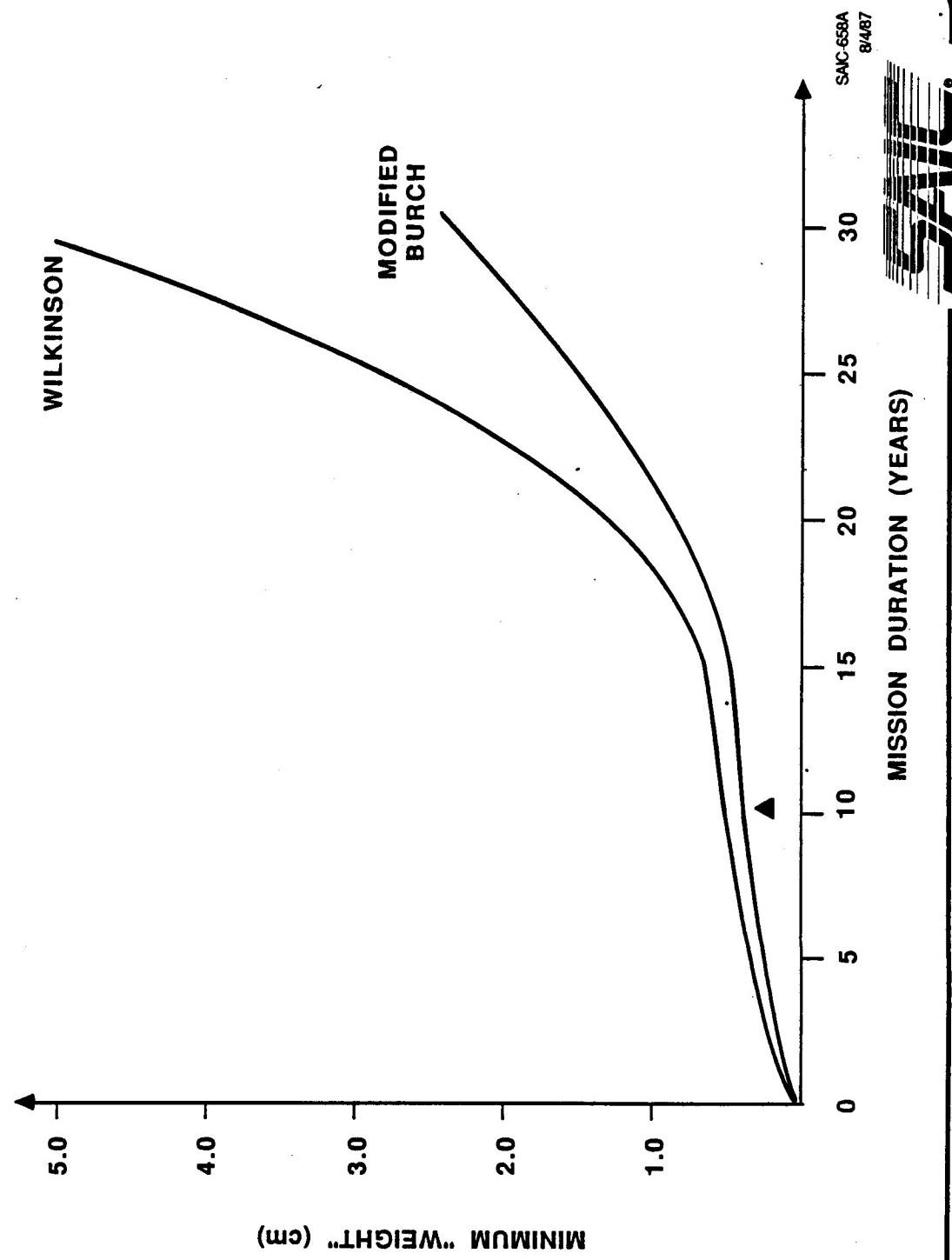
**WILKINSON MORE SENSITIVE TO MISSION RISK
THAN MODIFIED BURCH**



**GP REVEALS DIVERGENT SENSITIVITIES TO MISSION
DURATION IN 20-30 YEAR RANGE**

THE OPTIMAL DESIGN SENSITIVITY TO MISSION DURATION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS SHOWN. EXCEPT FOR SHORT DURATION MISSIONS, THE WILKINSON CURVE DOMINATES IN AN INCREASING FASHION.

**GP REVEALS DIVERGENT SENSITIVITIES TO MISSION DURATION
IN 20 - 30 YEAR RANGE**



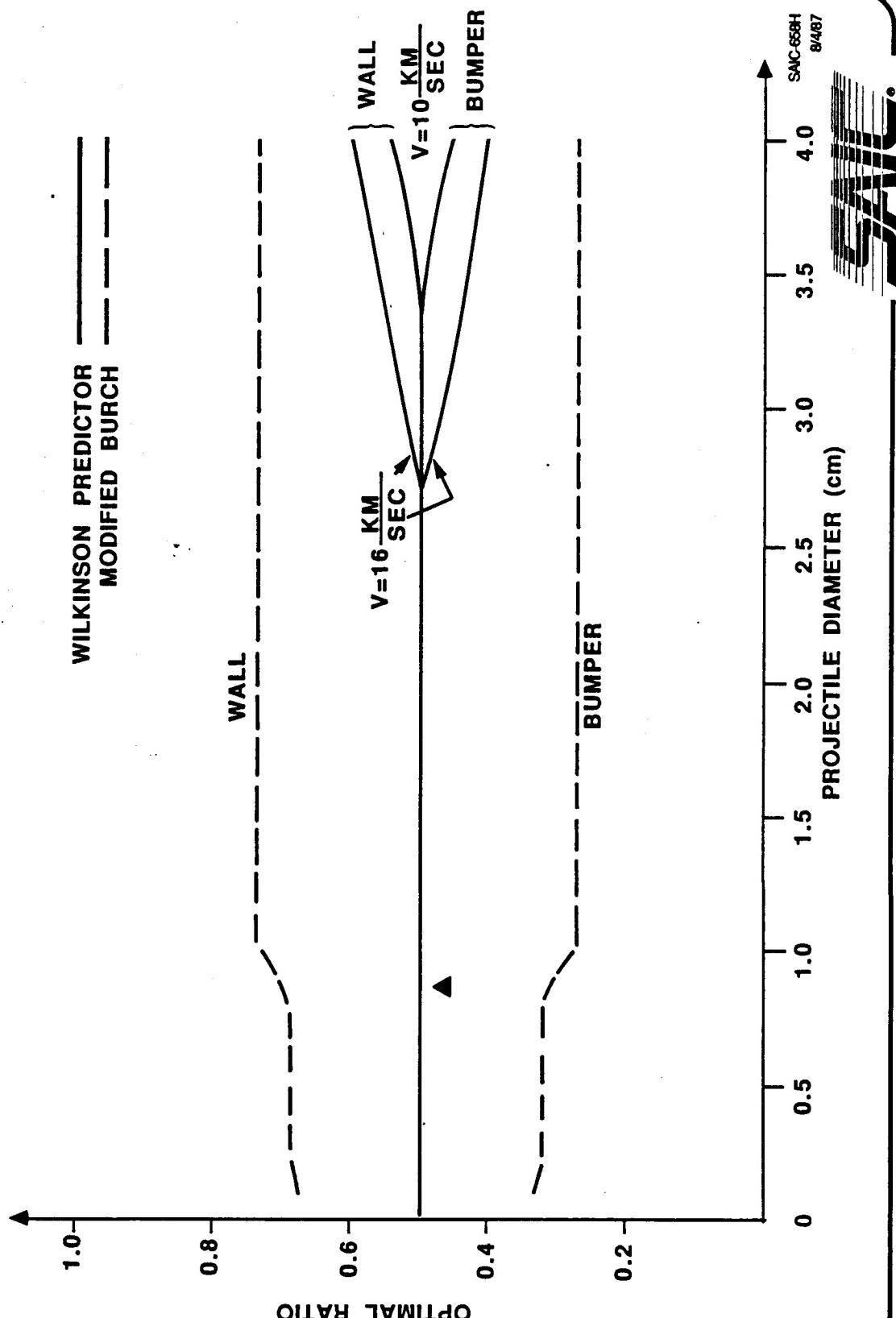
SAC-658A
8/4/87



GP DEFINES OPTIMAL DESIGN DISTRIBUTIONS

THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS IS DEPICTED . THIS IS THE RATIO BETWEEN THE OPTIMAL BUMPER (OR WALL) THICKNESS AND THE TOTAL OPTIMAL THICKNESS. FOR THE MODIFIED BURCH PREDICTOR, THIS RATIO INDICATES AN OPTIMAL DISTRIBUTION OF 27%-33% BUMPER, 73%-67% WALL. FOR THE WILKINSON PREDICTOR, THE OPTIMAL DISTRIBUTION IS 50% BUMPER, 50% WALL, EXCEPT FOR LARGE DIAMETER PROJECTILES OR HIGHER VELOCITIES. IN THESE REGIONS, THE OPTIMAL DISTRIBUTION IS SKEWED TOWARD THE WALL THICKNESS.

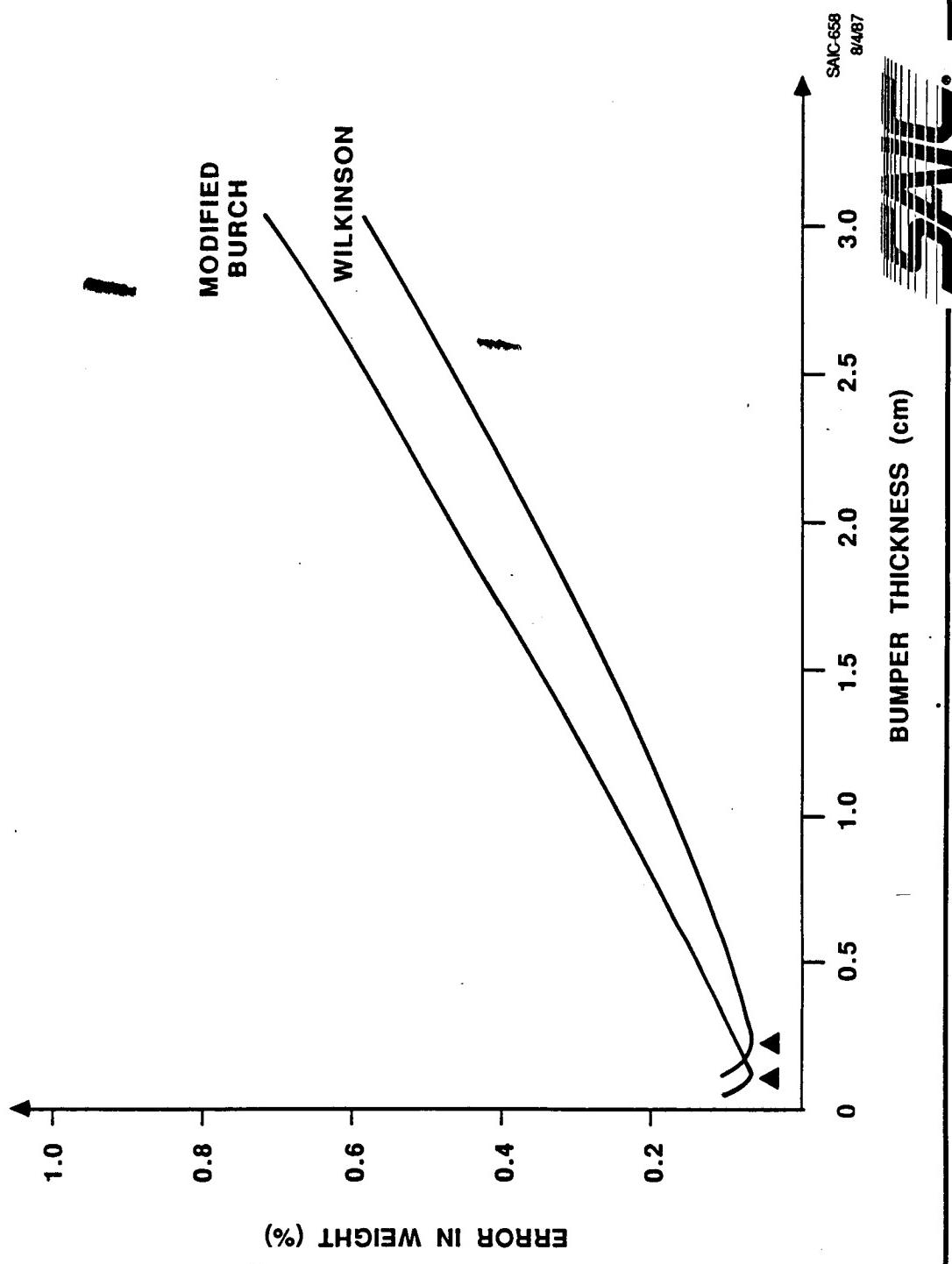
GP DEFINES OPTIMAL DESIGN DISTRIBUTIONS



**LOW ERRORS ASSOCIATED WITH TWO
DEGREE-OF-DIFFICULTY APPROXIMATION TO CMC WEIGHT**

SHOWN IS THE EFFECT OF BUMPER THICKNESS ON THE ERROR IN DESIGN WEIGHT ASSOCIATED WITH APPROXIMATING THE FIVE DEGREE-OF-DIFFICULTY GEOMETRIC PROGRAMMING PROBLEM WITH A TWO-TERM FUNCTION FOR THE MODIFIED BURCH AND WILKINSON SUBPREDICTORS. AS IN THE NYSMITH CASE, THE ERRORS ASSOCIATED WITH THIS APPROXIMATION ARE NEGLIGIBLE.

LOW ERRORS ASSOCIATED WITH TWO DEGREE-OF-DIFFICULTY APPROXIMATION TO CMC WEIGHT



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SECTION V

**GEOMETRIC PROGRAMMING APPLIED TO
THE BOEING PREDICTOR.**

BM30-8/21



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WHAT YOU WILL SEE IN SECTION V

- BASELINE DESIGN PARAMETERS FOR THE BOEING PREDICTOR
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING PREDICTOR
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
 - PROJECTILE VELOCITY
 - BUMPER/WALL SEPARATION
 - PROJECTILE DIAMETER
 - MISSION RISK
 - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER

BM5-10/13



BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE BOEING PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 16% BUMPER, 84% WALL.

BM03-99



BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS

$P_0 = 0.97$	(PROBABILITY OF NO PENETRATION)
$T = 10 \text{ YRS}$	(MISSION DURATION)
$A_d = 574 \text{ m}^2$	(DEBRIS AREA)
$A_m = 403 \text{ m}^2$	(METEOROID AREA)
$\text{Alt} = 500 \text{ km}$	(AVERAGE ALTITUDE)
$V_m = 20 \text{ km/sec}$	(AVERAGE METEOROID VELOCITY)
$V_D = 10 \text{ km/sec}$	(AVERAGE DEBRIS VELOCITY)
$\rho_m = 0.5 \text{ gm/cm}^3$	(METEOROID DENSITY)
$\rho_D = 2.81 \text{ gm/cm}^3$	(DEBRIS DENSITY)
$S = 10 \text{ cm}$	(BUMPER/WALL SEPARATION)
$\rho_1 = 2.8 \text{ gm/cm}^3$	
$E_1 = 7.239 \times 10^{11} \text{ gm/cm}\cdot\text{sec}^2$	
$Sy_1 = 7344000 \text{ lb/ft}^2$	(51 Ksi)
$\rho_2 = \rho_1$	
$Sy_2 = Sy_1$	
$L_2 = 0.401$	
$\theta = 0 \text{ degrees}$	

BM06-8/21



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BASELINE DESIGN PARAMETERS (CONT'D)

OPTIMAL DESIGN (BALLISTIC LIMIT)

BUMPER

$t_{10} = 0.09 \text{ cm (.04 in)}$

WALL

$t_{20} = 0.49 \text{ cm (.19 in)}$

CMC weight = 2979 Kg (6554 lb)

BM06A-8/21

SAC

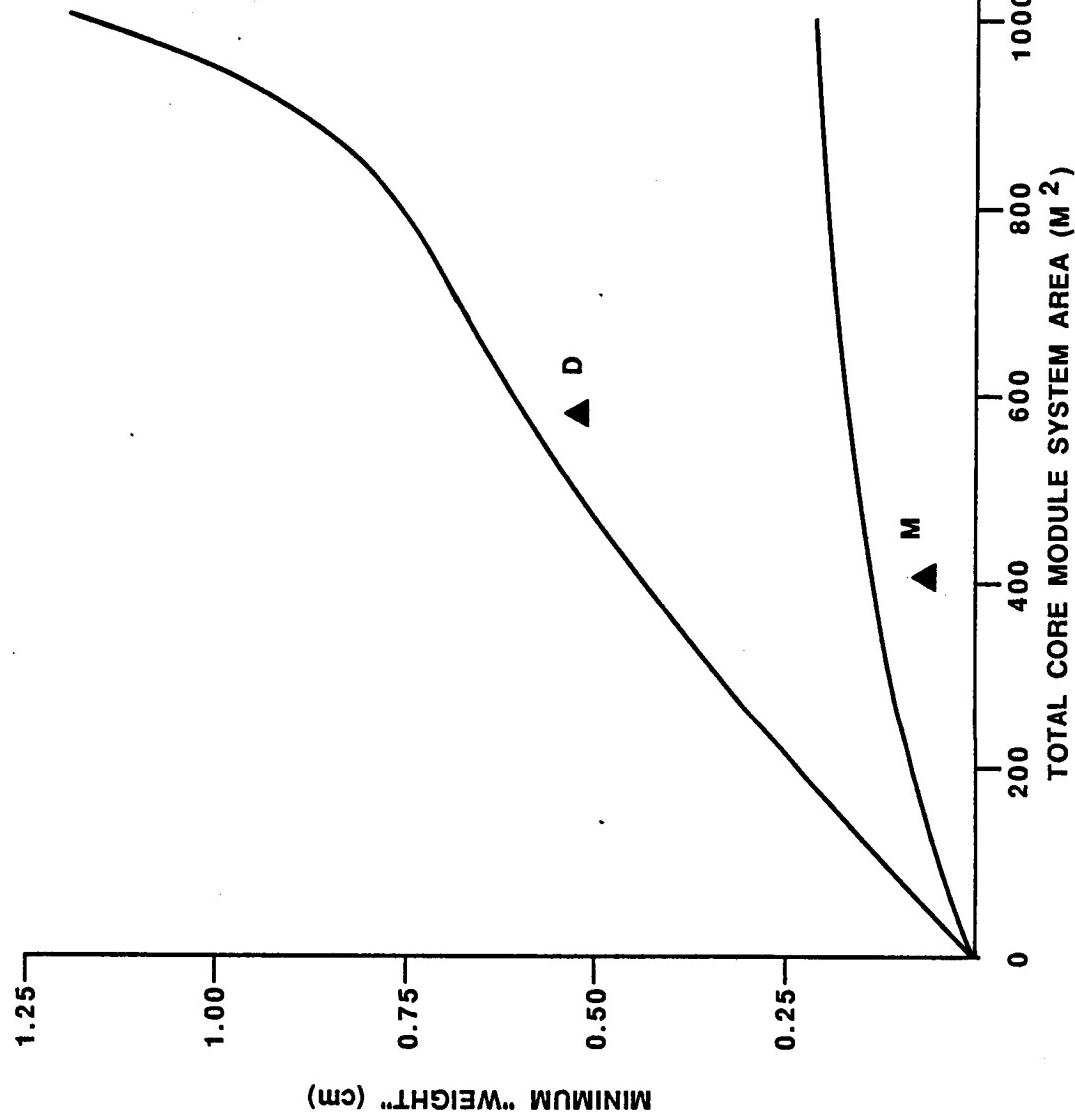
DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT

SHOWN IS THE EFFECT OF CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID SCENARIOS OF THE BOEING PREDICTOR. NOTE THAT EVEN THOUGH THE METEOROID PROJECTILE DENSITY WAS ASSUMED TO BE 2.81 GM/CUBIC CM (BURCH HAS NO DENSITY PARAMETER), THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN.

BM07-8/11

SAIC™

**DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE
ESTIMATE OF METEOROID EFFECT**



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8/11/87



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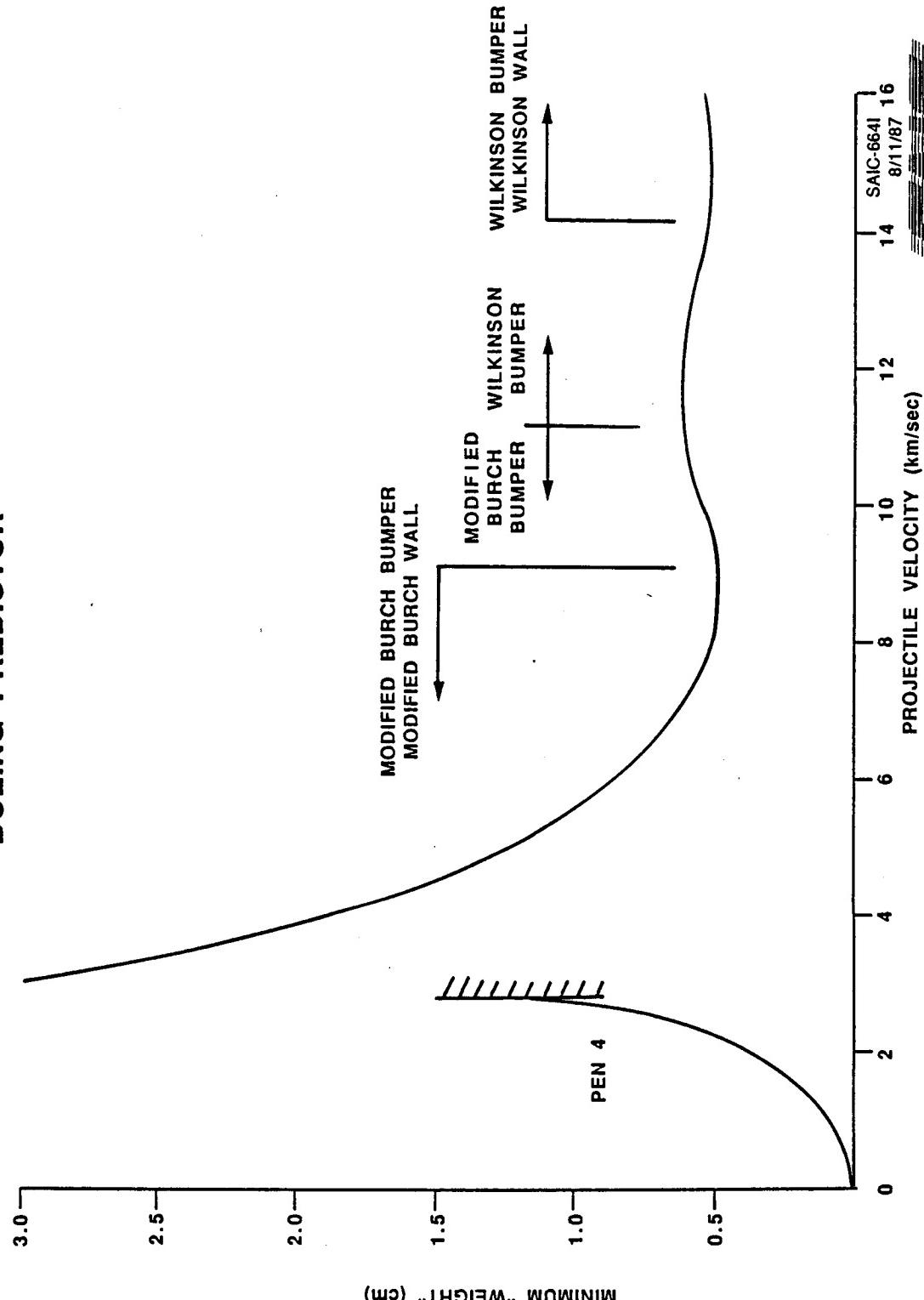
GP REVEALS COMPLEX DESIGN SENSITIVITY TO VELOCITY FOR BOEING PREDICTOR

THE EFFECT OF PROJECTILE VELOCITY ON OPTIMAL DESIGN IS SHOWN FOR THE BOEING PREDICTOR. THE PEN4 PREDICTOR IS SEGREGATED FROM THE OTHER TWO BOEING PREDICTORS AS IT IS ONLY VALID UP TO 2.8 km/sec. ON COMPARISON WITH THE CORRESPONDING TRADE FOR THE THREE BOEING SUBPREDICTORS, IT IS EASY TO SEE THAT THE MODIFIED BURCH OPTIMAL DESIGN DOMINATES BETWEEN 2.8 km/sec AND 9 km/sec, AND THE WILKINSON OPTIMAL DESIGN DOMINATES FROM 14 TO 16 km/sec. BETWEEN 9 AND 11 km/sec, THE MODIFIED BURCH OPTIMAL BUMPER DESIGN IS CHOSEN ALONG WITH THE WILKINSON WALL DESIGN INDUCED BY THIS BUMPER. FROM 11 TO 14 km/sec, THE ROLES OF THE TWO PREDICTORS ARE REVERSED.

BM08-8/11



**GP REVEALS COMPLEX DESIGN SENSITIVITY TO VELOCITY FOR
BOEING PREDICTOR**



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8/11/87

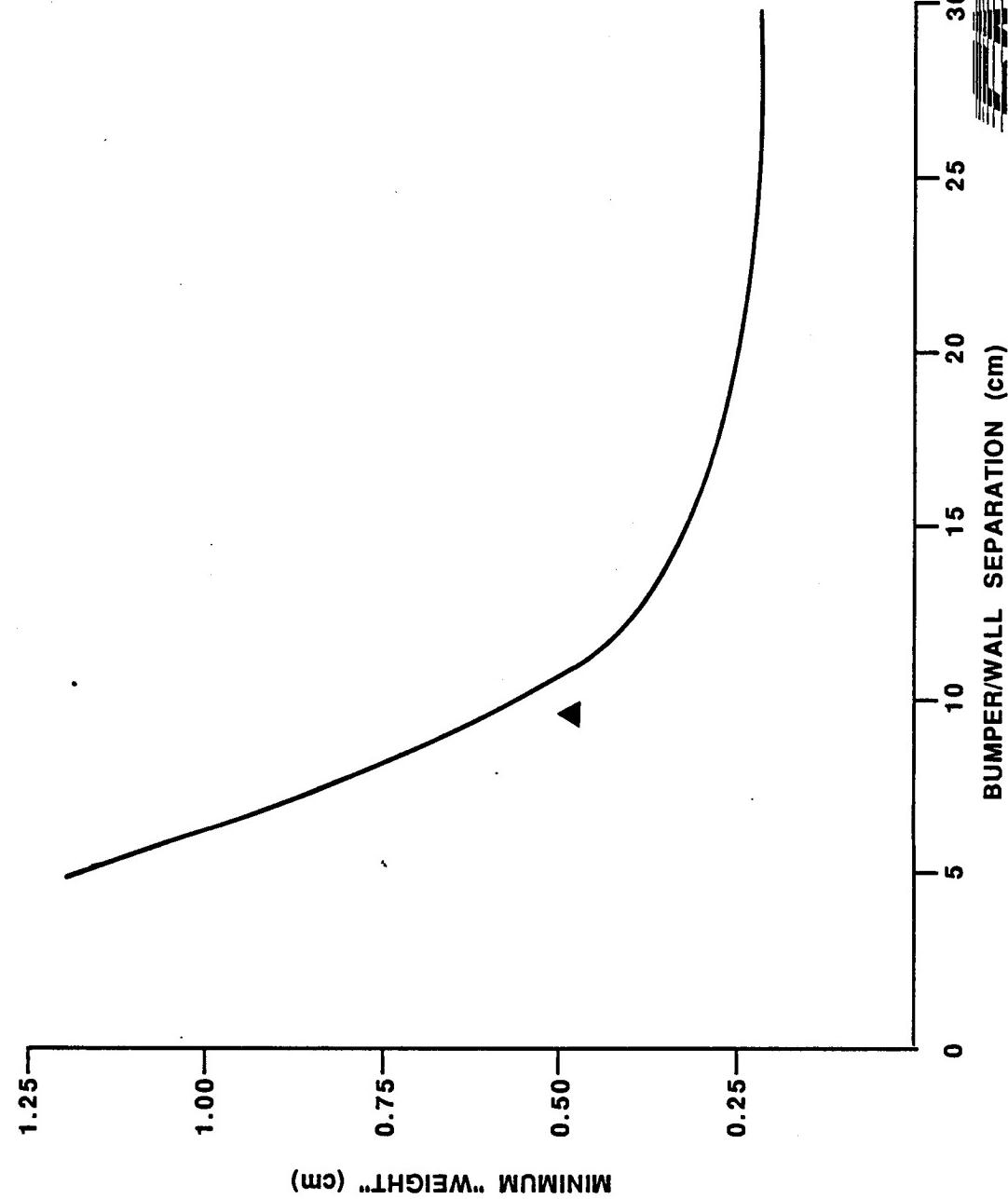
**GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION
FOR THE BOEING PREDICTOR**

SHOWN IS THE DESIGN SENSITIVITY TO BUMPER/WALL SEPARATION FOR THE BOEING PREDICTOR. NOTE THE LARGE INCENTIVE (A REDUCTION IN DESIGN OF 40%) FOR INCREASING THE BUMPER/WALL SEPARATION BY 50% TO 15CM.

BM09-8/11



**GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION
FOR THE BOEING PREDICTOR**



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8/11/87



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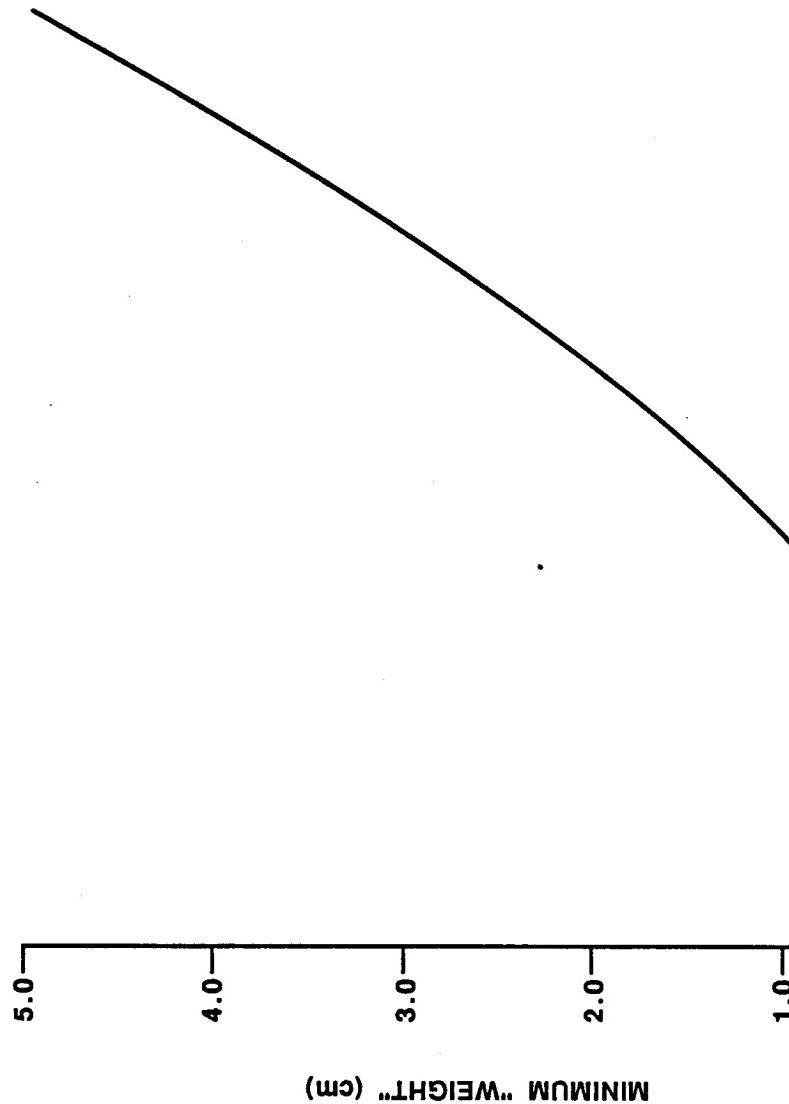
LARGE DIAMETERS HEAVILY TAX DESIGN
FOR BOEING PREDICTOR

SHOWN IS THE SENSITIVITY OF OPTIMAL DESIGN TO PROJECTILE DIAMETER
FOR THE BOEING PREDICTOR. NOTE THE LARGE SENSITIVITY FOR PRO-
JECTILE DIAMETERS GREATER THAN ABOUT 1CM, WHERE THE SLOPES
INCREASE TO 2-3.

BM10-8/11



LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR



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8/11/87



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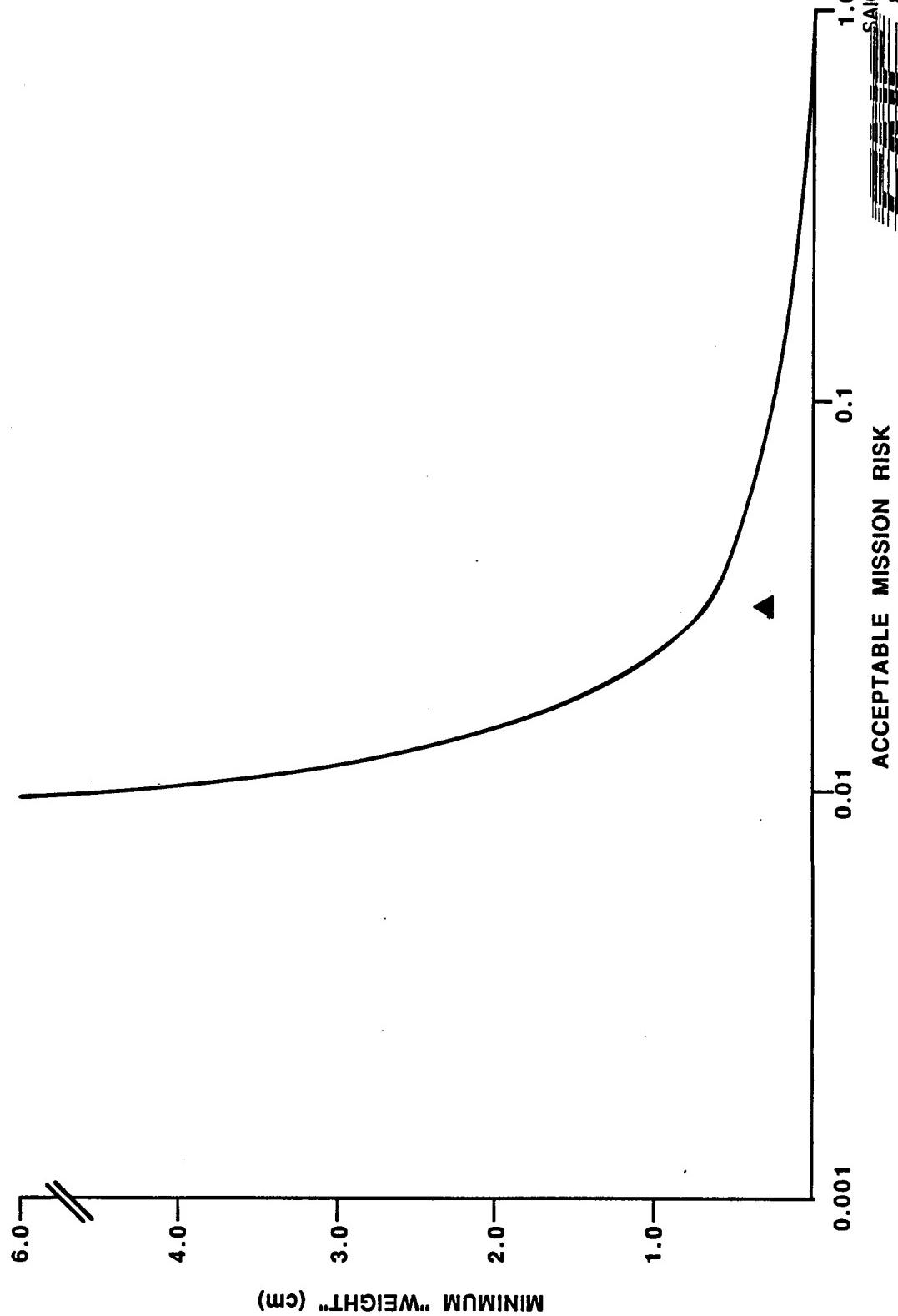
LARGE DESIGN PENALTY INDUCED BY INCREASE IN
PROBABILITY OF NO PENETRATION: BOEING PREDICTOR

THE EFFECT OF ACCEPTABLE MISSION RISK ON OPTIMAL DESIGN IS SHOWN
FOR THE BOEING PREDICTOR. NOTE THE DRASTIC INCREASE IN OPTIMAL
DESIGN FOR PROBABILITY OF NO PENETRATION ABOVE 0.97.

BM11-8/11



LARGE DESIGN PENALTY INDUCED BY INCREASE IN
PROBABILITY OF NO PENETRATION: BOEING PREDICTOR



1.0
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8/11/87



ACCEPTABLE MISSION RISK

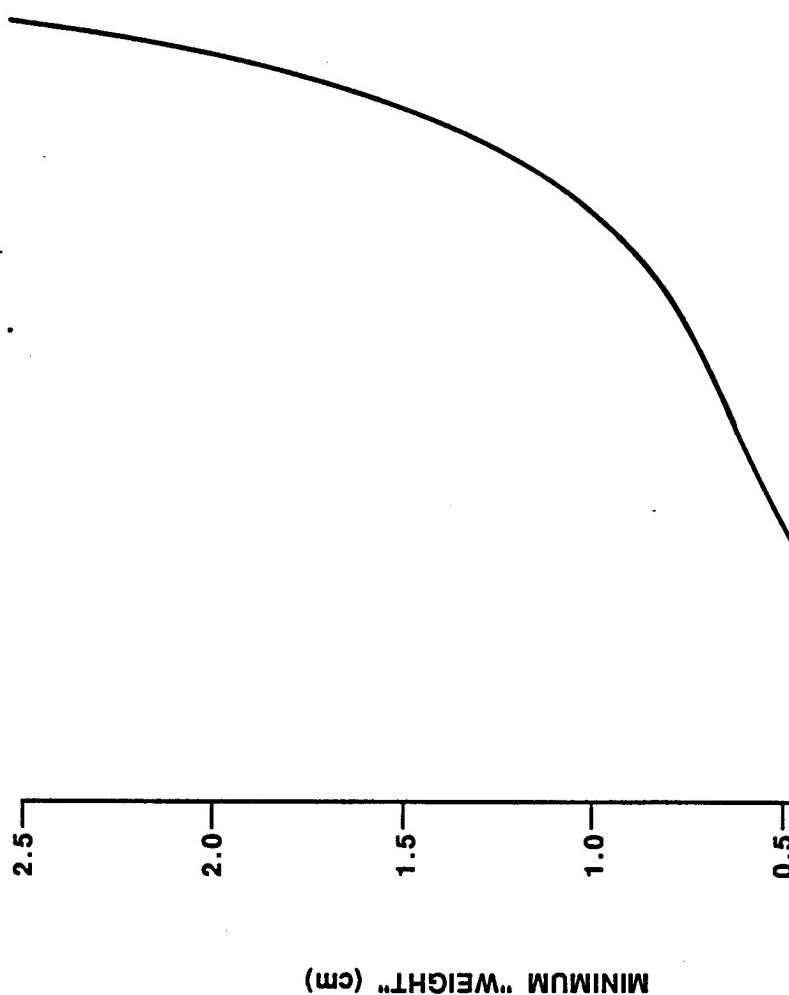
SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION
MISSIONS: BOEING PREDICTOR

THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR THE BOEING PREDICTOR IS SHOWN. THE INFLECTION AT 15 YEARS, AND THE SHARP INCREASE IN SLOPE AT ABOUT 22 YEARS RAISE SERIOUS DESIGN QUESTIONS FOR MISSION PLANNERS ABOUT LONG-DURATION MISSIONS.

BM12-8/11



**SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION
MISSIONS: BOEING PREDICTOR**



SAIC-664D
8/11/87



SAIC

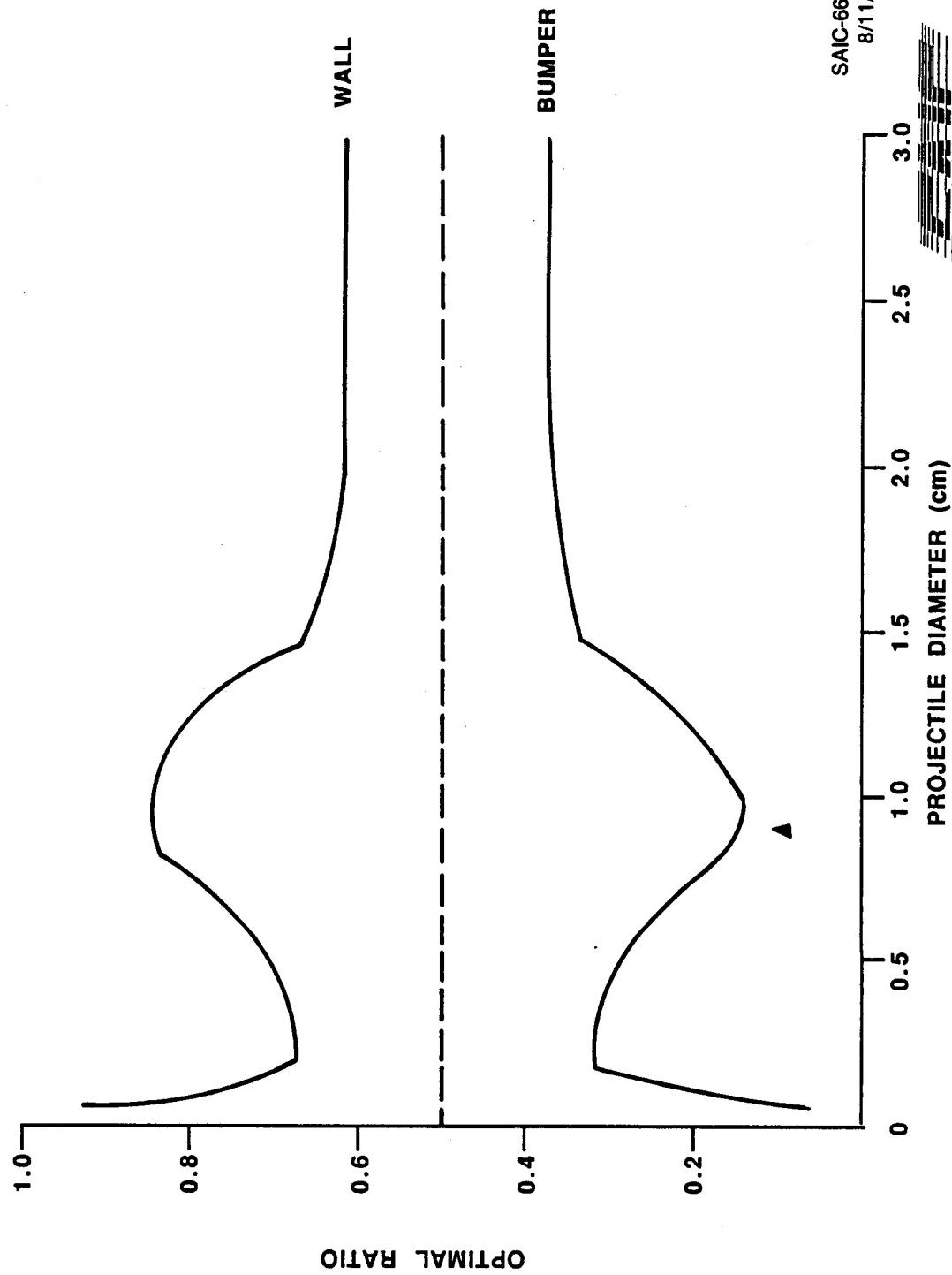
GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR

THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER IS DEPICTED FOR THE BOEING PREDICTOR. THIS IS THE RATIO OF OPTIMAL BUMPER (WALL) THICKNESS TO TOTAL OPTIMAL THICKNESS, AND IS QUITE NON-LINEAR (AND NONCONSTANT). THIS NONLINEARITY HAS TO DO WITH THE INTERACTION OF THE MODIFIED BURCH AND WILKINSON PREDICTORS.

BM13-8/11



**GP PROVIDES OPTIMAL DISTRIBUTION
FOR BOEING PREDICTOR**



SAIC-664C
8/11/87

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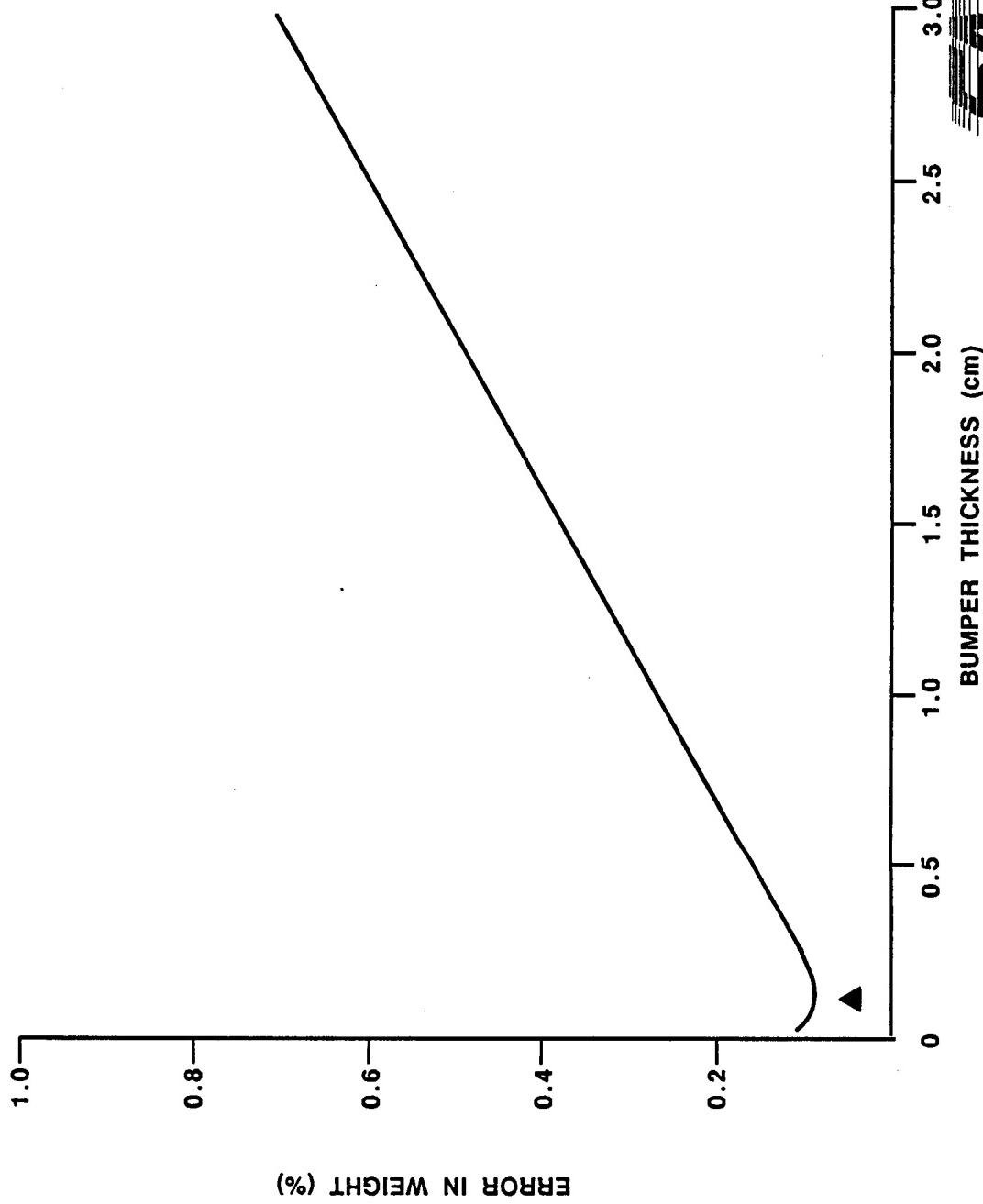
SMALL ERRORS ASSOCIATED WITH REDUCTION OF DEGREE-OF-DIFFICULTY FOR BOEING PREDICTOR

THE ERROR IN CORE MODULE CONFIGURATION WEIGHT AS A FUNCTION OF BUMPER THICKNESS IS SHOWN FOR THE BOEING PREDICTOR. THIS REPRESENTS THE ERROR INDUCED BY REDUCING THE GP OPTIMIZATION PROBLEM FROM 5 DEGREES-OF-DIFFICULTY TO TWO. NOTE THAT THE ERROR IS NEGIGIBLE IN A LARGE NEIGHBORHOOD OF THE BASELINE DESIGN.

BM14-8/11



**SMALL ERRORS ASSOCIATED WITH REDUCTION OF
DEGREE-OF-DIFFICULTY FOR BOEING PREDICTOR**



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8/11/87

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SECTION VI

**GEOMETRIC PROGRAMMING APPLIED TO
THE VELOCITY-INTEGRATED BOEING
PREDICTOR.**

BM31-8/21

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WHAT YOU WILL SEE IN SECTION VI

- ALGORITHM AND BASELINE DESIGN PARAMETERS FOR THE VELOCITY-INTEGRATED BOEING SUBPREDICTORS
- A COMPARISON OF METEOROID AND DEBRIS SCENARIOS FOR THE BOEING SUBPREDICTORS
- THE SENSITIVITY OF OPTIMAL DESIGN TO ORBITAL INCLINATION
- DESIGN TRADES, INCLUDING MINIMUM "WEIGHT" VERSUS:
 - PROJECTILE VELOCITY
 - BUMPER/WALL SEPARATION
 - PROJECTILE DIAMETER
 - MISSION RISK
 - MISSION DURATION
- THE OPTIMAL RATIO FOR BUMPER AND WALL AS A FUNCTION OF PROJECTILE DIAMETER
- COST EXCURSIONS
- SUMMARY OF PREDICTOR RESULTS

BM6 10/13



BASELINE DESIGN PARAMETERS

THE BASELINE DESIGN PARAMETERS AS REQUIRED FOR THE VELOCITY-INTEGRATED BOEING PREDICTOR ARE SHOWN. NOTE THAT THE BASELINE OPTIMAL DISTRIBUTION IS 21% BUMPER, 79% WALL.

BM04-99

SAC

BASELINE DESIGN PARAMETERS

DESIGN ASSUMPTIONS

P_0	=	0.97	(PROBABILITY OF NO PENETRATION)
T	=	10 yrs	(MISSION DURATION)
A_d	=	574 m^2	(DEBRIS AREA)
A_m	=	403 m^2	(METEOROID AREA)
Alt	=	500 km	(AVERAGE ALTITUDE)
ρ_m	=	0.5 gm/cm^3	(METEOROID DENSITY)
ρ_D	=	2.81 gm/cm^3	(DEBRIS DENSITY)
S	=	10 cm	(BUMPER/WALL SEPARATION)
ρ_1	=	2.81 gm/cm^3	
E_1	=	$7.239 \times 10^{11} \text{ gm/cm}\cdot\text{sec}^2$	
sy_1	=	7344000 lb/in^2 (51 ksi)	
ρ_2	=	ρ_1	
sy_2	=	sy_1	
L_2	=	0.401	
θ	=	0 degrees	

OPTIMAL DESIGN (BALLISTIC LIMIT)	
BUMPER	
t_{10}	= 0.16cm (0.06 in)
WALL	
t_{20}	= 0.59 cm (0.23 in)
CMC	= 3837 Kg (8441 lb)
weight	

BM07-8/21

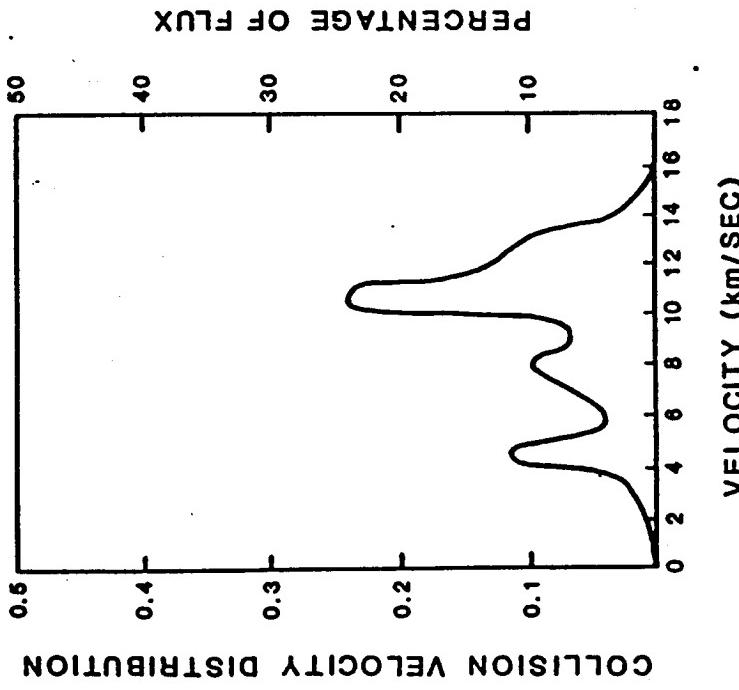
VELOCITY PROBABILITY DISTRIBUTIONS

SHOWN IS THE 500km VELOCITY PROBABILITY DISTRIBUTION FOR 30 AND 60 DEGREE INCLINATIONS FROM DON KESSLER'S JSC-20001. NOTE THAT THE 60 DEGREE INCLINATION DISTRIBUTION IS HIGHLY SKEWED TOWARD THE HIGHER VELOCITIES.

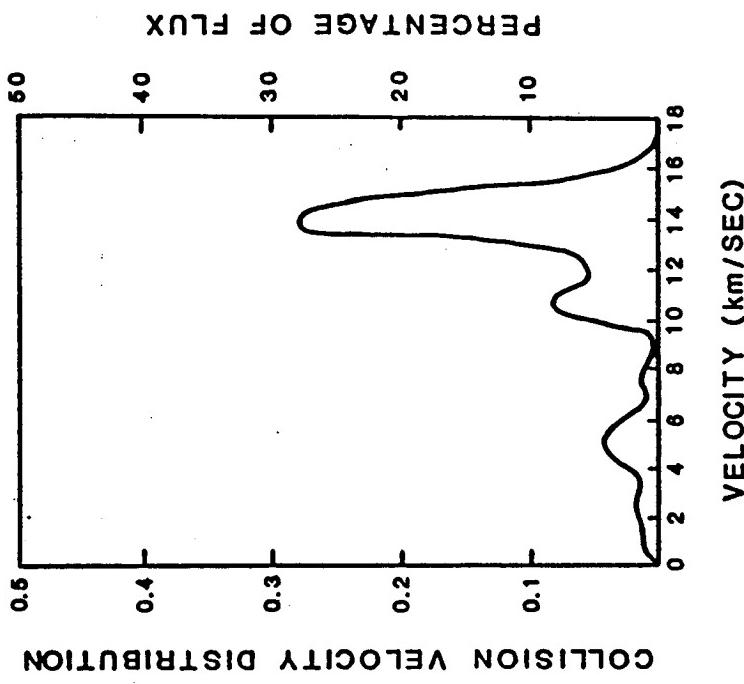
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VELOCITY PROBABILITY DISTRIBUTIONS

ALTITUDE: 500 km
INCLINATION: 30°



ALTITUDE: 500 km
INCLINATION: 60°



SAIL®

METEOROID VELOCITY PROBABILITY DISTRIBUTION

AN APPROXIMATE VELOCITY PROBABILITY DISTRIBUTION FOR THE METEOROID SCENARIO IS SHOWN. AVERAGE VELOCITY IS ROUGHLY 20 KM/SEC. THIS DISTRIBUTION IS REFERENCED IN BURT COUR-PALAIS "METEOROID ENVIRONMENT MODEL - 1969 (NEAR-EARTH TO LUNAR SURFACE," NASA SP-8013, MARCH 1969.

BM14-8/21



METEOROID VELOCITY PROBABILITY DISTRIBUTION

.28

PROBABILITY FOR MIDPOINT OF 3 km/sec INTERVAL

.24
.20
.16
.12
.08
.04
0

AVERAGE VELOCITY,
20 km/sec

ATMOSPHERIC ENTRY VELOCITY, km/sec

SAIL

80
70
60
50
40
30
20
10
0

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ALGORITHM FOR VELOCITY-INTEGRATED BOEING PREDICTOR

- (1) DETERMINE VELOCITY INTERVALS.
- (2) FOR MIDPOINT OF INTERVAL, DETERMINE OPTIMAL DESIGN FOR BOEING PREDICTOR.
- (3) MULTIPLY OPTIMAL DESIGN BY APPROPRIATE VELOCITY PROBABILITY AT INTERVAL MIDPOINT; THEN MULTIPLY BY INTERVAL LENGTH.
- (4) SUM THE PRODUCT IN (3) OVER THE ENTIRE RANGE OF VELOCITIES TO DETERMINE THE OVERALL OPTIMAL DESIGN.



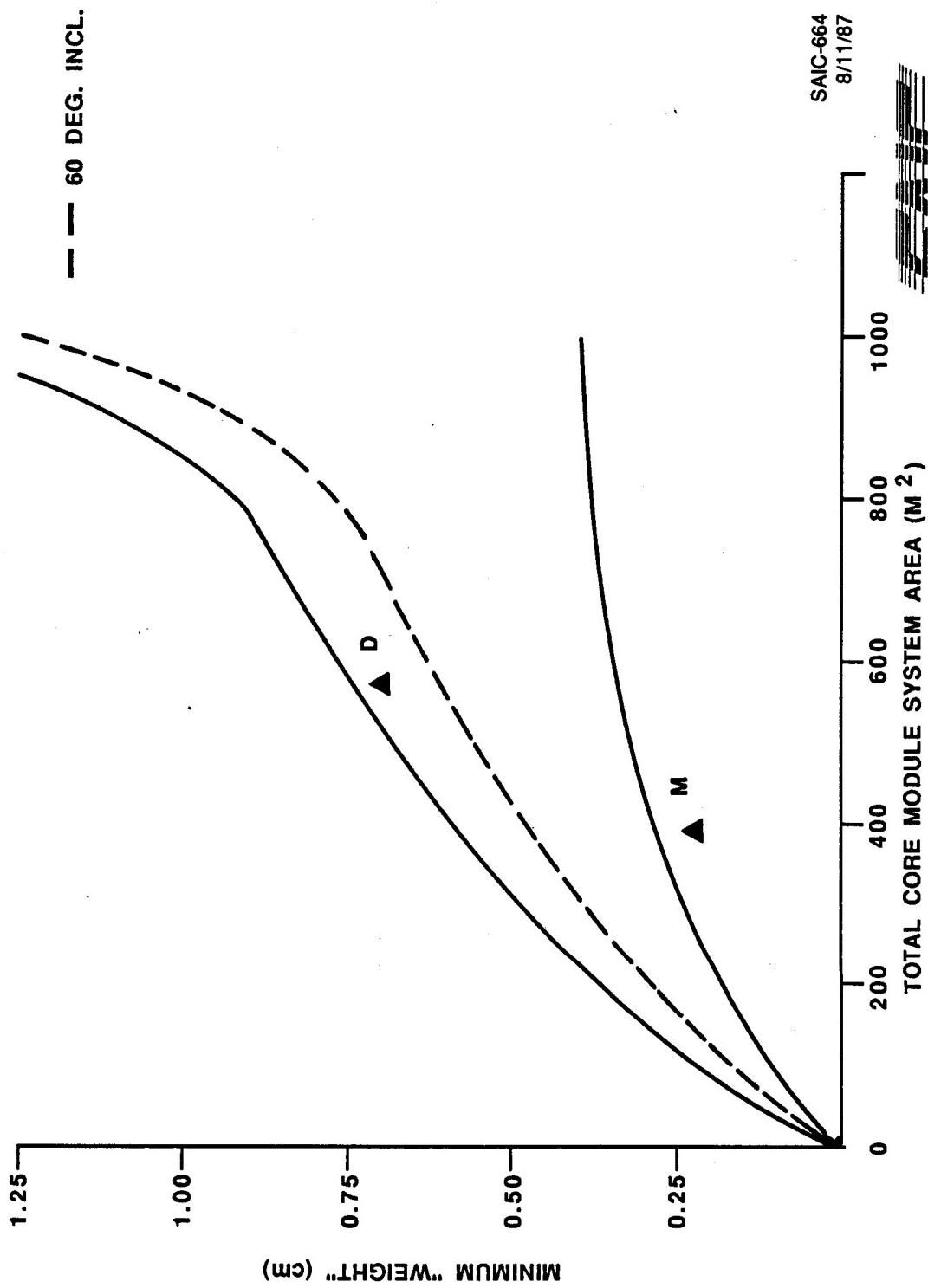
DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE ESTIMATE OF METEOROID EFFECT

SHOWN IS THE EFFECT OF CORE MODULE SYSTEM AREA ON OPTIMAL DESIGN FOR THE DEBRIS AND METEOROID SCENARIOS OF THE BOEING PREDICTOR FOR THE BASELINE 30 DEGREE INCLINATION AND A 60 DEGREE INCLINATION. NOTE THAT EVEN THOUGH THE METEOROID PROJECTILE DENSITY WAS ASSUMED TO BE 2.81 GM/CUBIC CM (BURCH HAS NO DENSITY PARAMETER), THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN. FURTHERMORE, NOTE THE 20% DECREASE IN DESIGN INDUCED BY A 60° INCLINATION.

BM01-8/11



DEBRIS ENVIRONMENT DOMINATES EVEN CONSERVATIVE
ESTIMATE OF METEOROID EFFECT



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8/11/87

SAIC

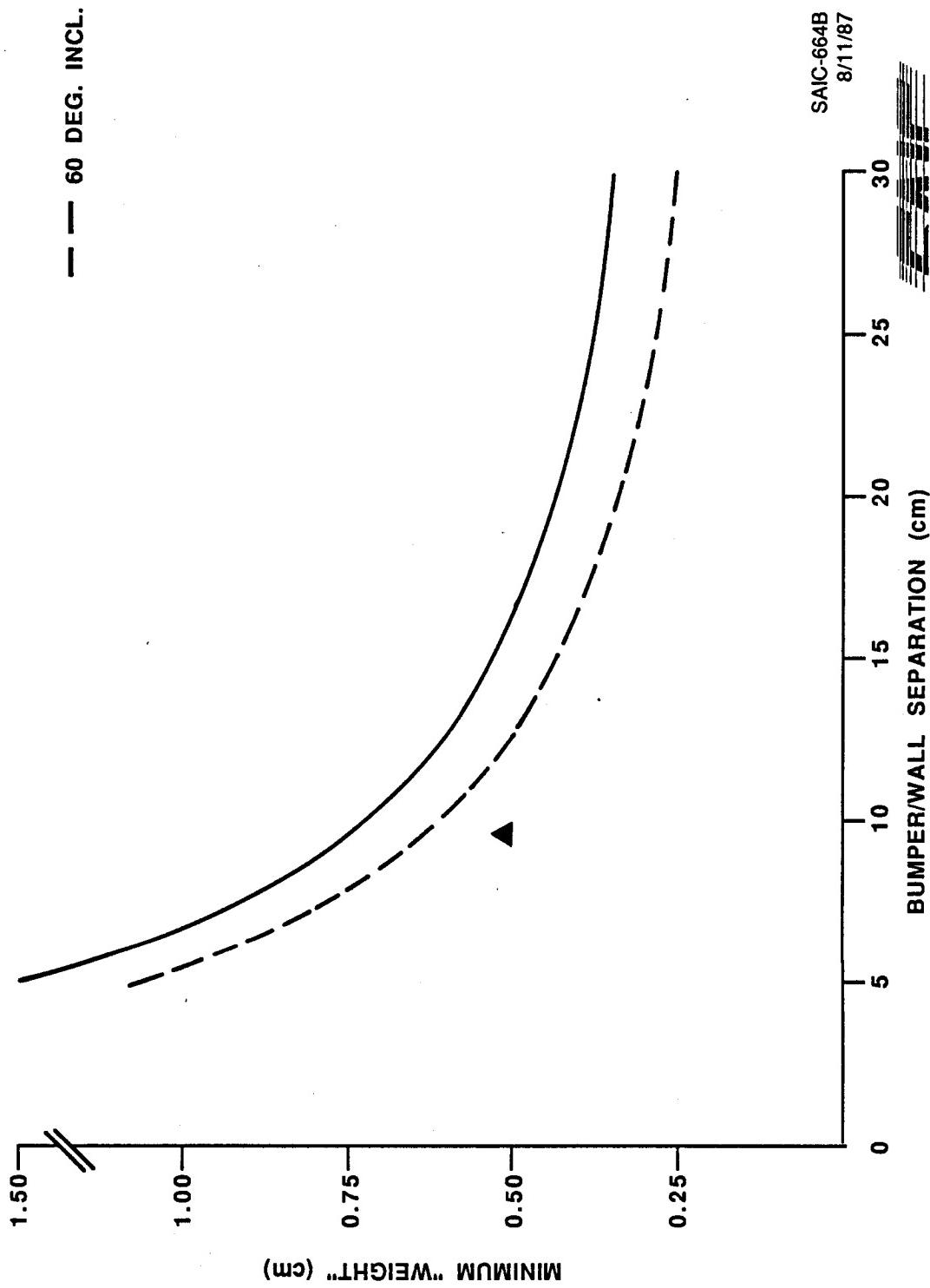
**GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION
FOR THE BOEING PREDICTOR**

THE DESIGN SENSITIVITY TO BUMPER/WALL SEPARATION FOR THE BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. NOTE THE LARGE INCENTIVE (A REDUCTION IN DESIGN OF 40%) FOR INCREASING THE BUMPER/WALL SEPARATION BY 50% TO 15 CM.

BM02-8/11



**GP SHOWS THE DESIRABILITY OF INCREASING SEPARATION
FOR THE BOEING PREDICTOR**



SAIC-664B
8/11/87



SAIC

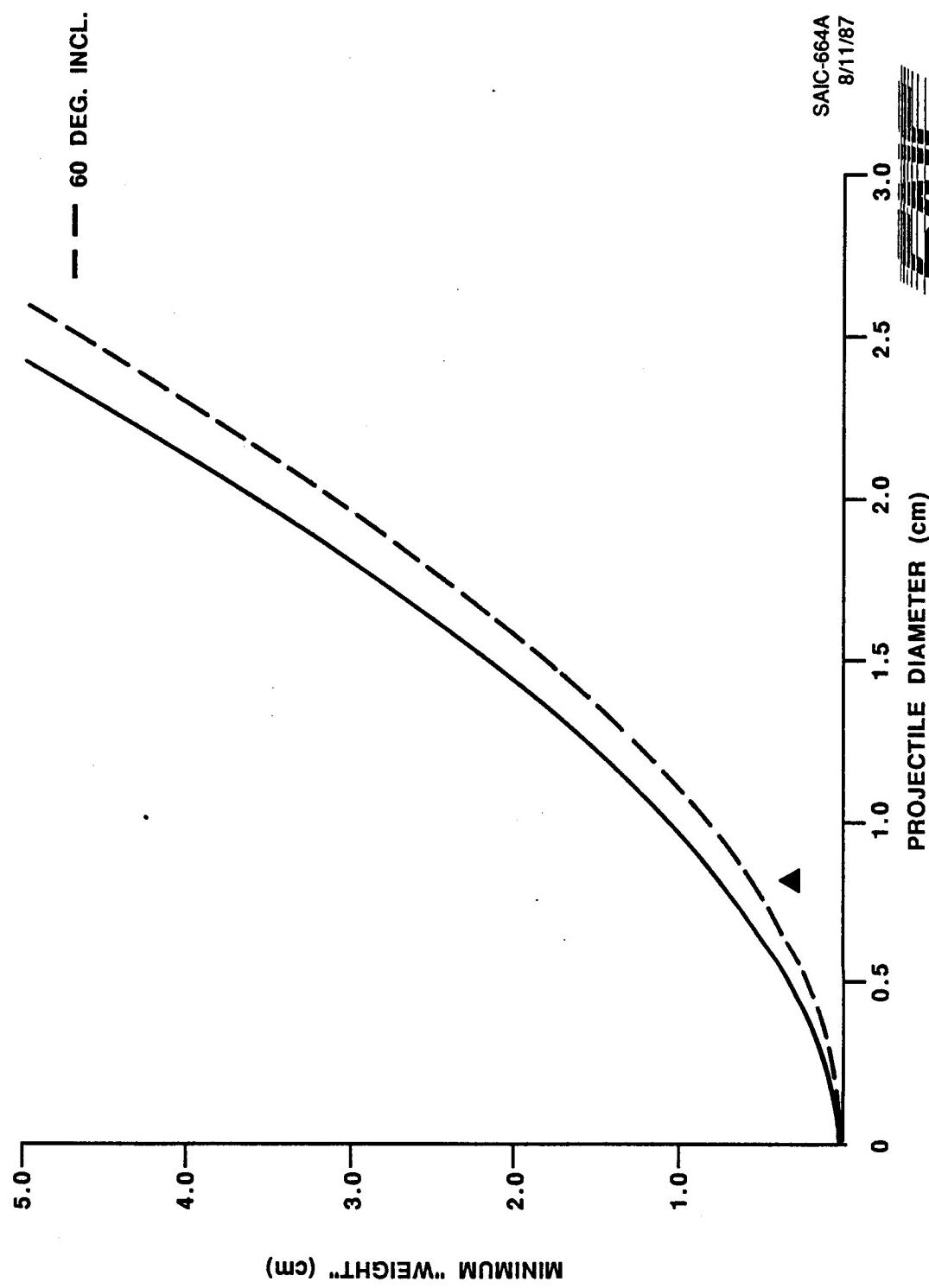
LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR

THE SENSITIVITY OF OPTIMAL DESIGN TO PROJECTILE DIAMETER FOR THE BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. NOTE THE LARGE SENSITIVITY FOR PROJECTILE DIAMETERS GREATER THAN ABOUT 1 CM, WHERE THE SLOPES INCREASE TO 2-3.

BM03-8/11



LARGE DIAMETERS HEAVILY TAX DESIGN FOR BOEING PREDICTOR



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8/11/87

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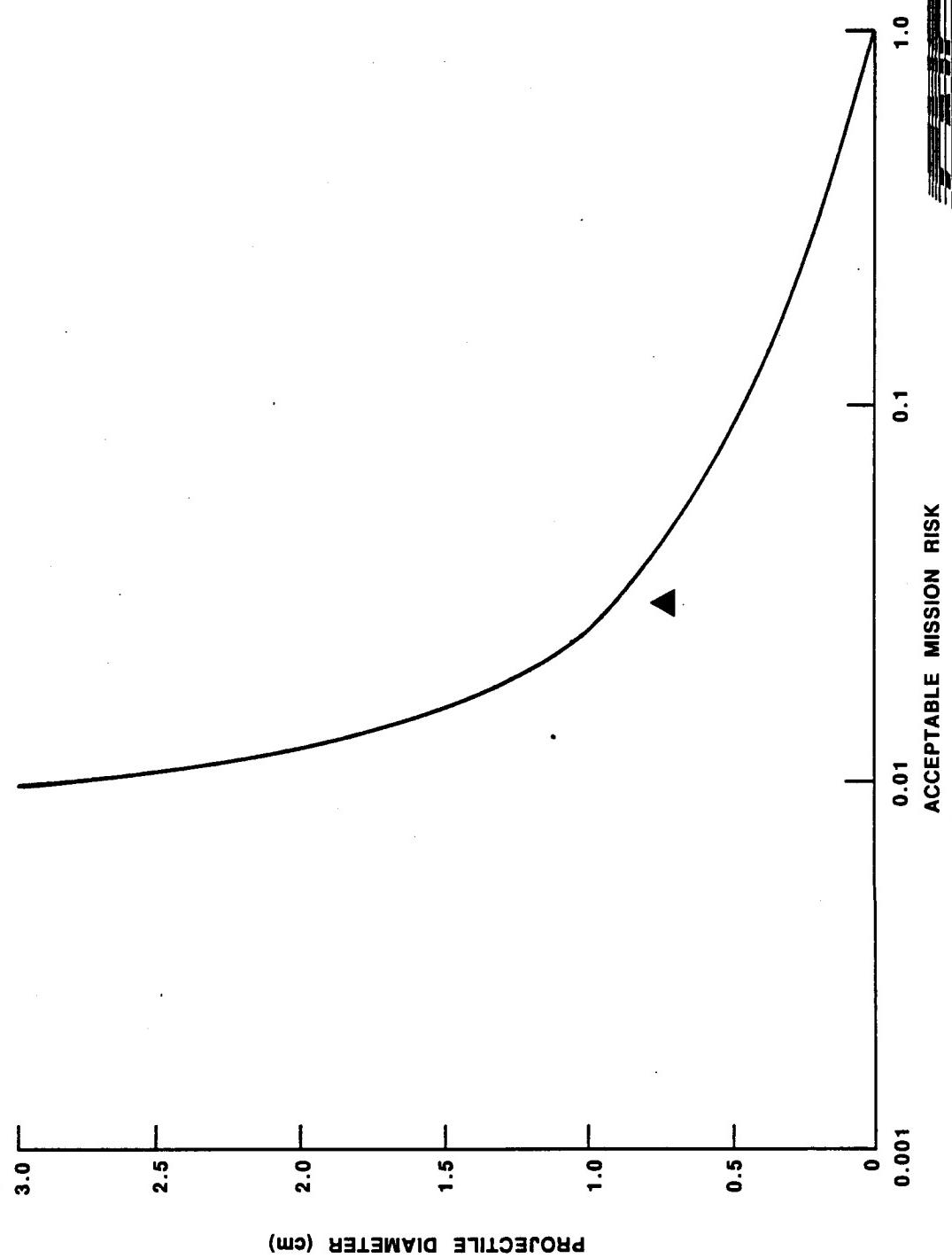
EFFECT OF MISSION RISK ON PROJECTILE DIAMETER

THE EFFECT OF MISSION RISK ON PROJECTILE DIAMETER IS SHOWN FOR THE DEBRIS SCENARIO. NOTE THAT AN INCREASE IN PROBABILITY OF NO PENETRATION FROM THE BASELINE INDUCES A LARGE INCREASE IN REQUIRED DESIGN.

BM12-8/21



EFFECT OF MISSION RISK ON PROJECTILE DIAMETER



SAF®

ACCEPTABLE MISISON RISK

0.01

0.1

0.001

1.0

**SIGNIFICANT DESIGN PENALTY INDUCED BY INCREASE IN
PROBABILITY OF NO PENETRATION: BOEING PREDICTOR**

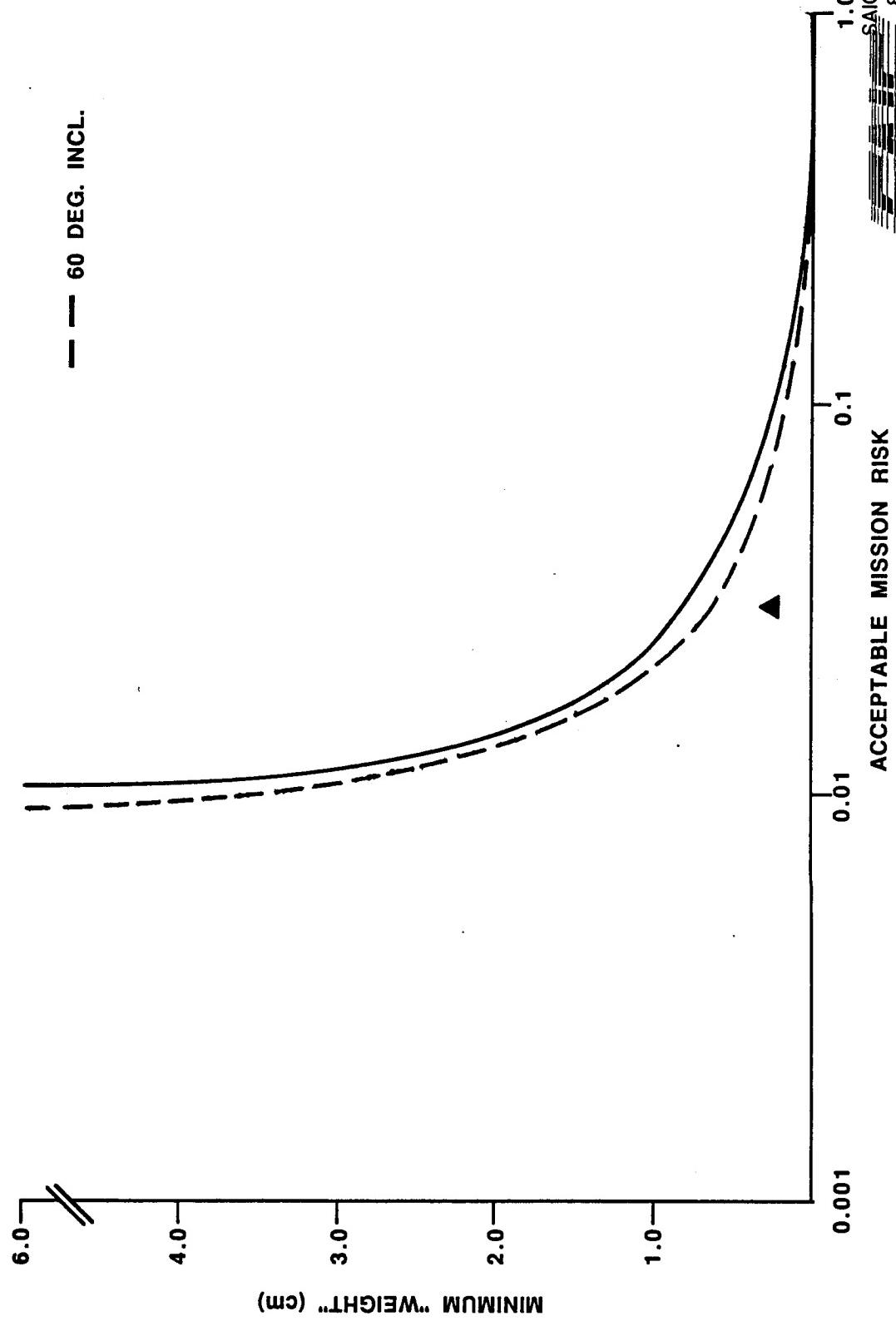
SHOWN IS THE EFFECT OF ACCEPTABLE MISSION RISK ON OPTIMAL DESIGN FOR THE BOEING PREDICTOR FOR 30 AND 60 DEGREE INCINERATIONS. NOTE THE DRASTIC INCREASE IN OPTIMAL DESIGN FOR PROBABILITY OF NO PENETRATION ABOVE 0.97.

BM04-8/11



**SIGNIFICANT DESIGN PENALTY INDUCED BY INCREASE IN
PROBABILITY OF NO PENETRATION: BOEING PREDICTOR**

— — 60 DEG. INCL.



SAIC-664H
8/11/87

SAIC

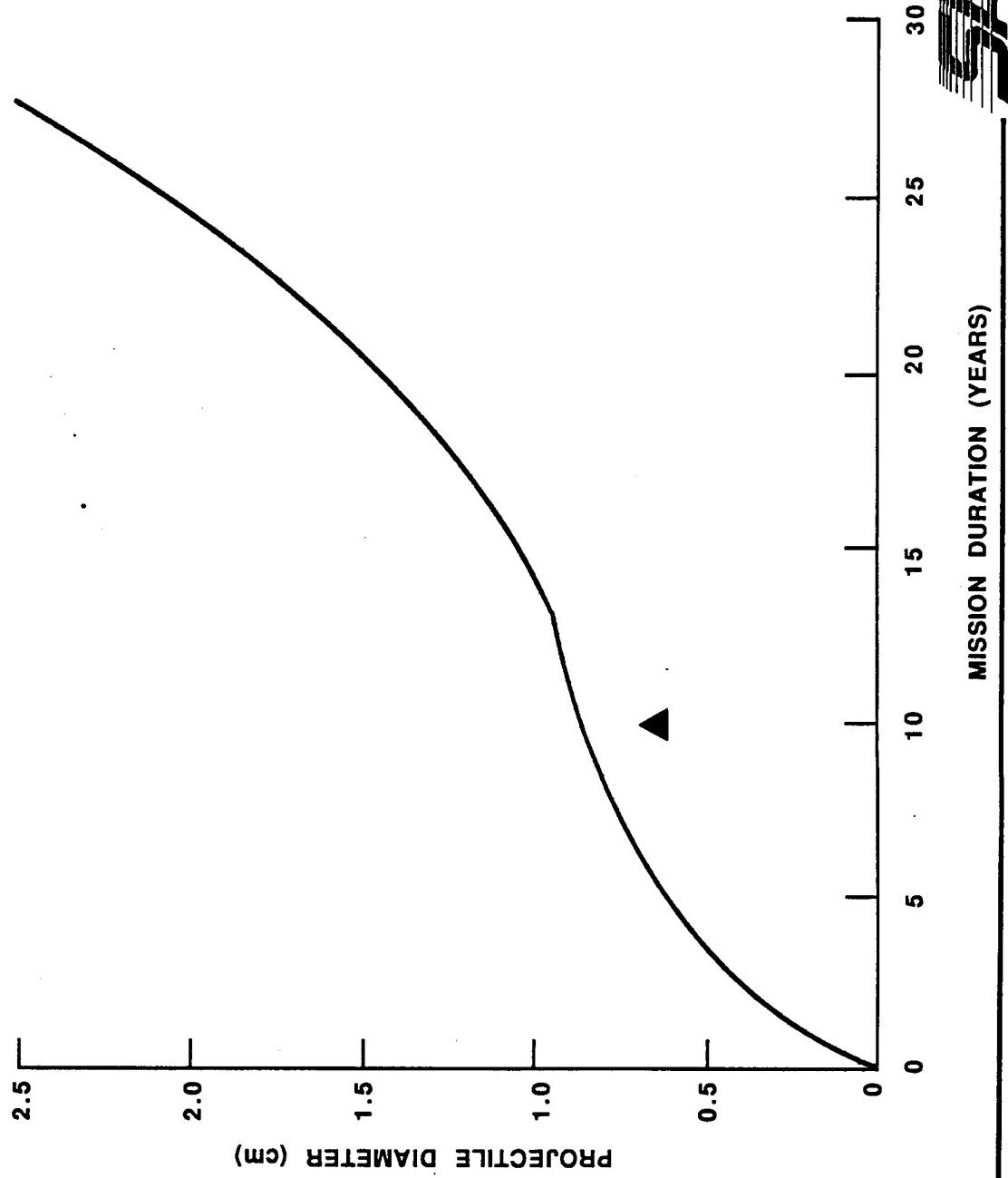
EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER

THE EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER IS SHOWN FOR THE DEBRIS SCENARIO. NOTE THE INFLECTION AT ABOUT 15 YEARS. THIS CORRESPONDS TO THE INFLECTION IN THE DEBRIS ENVIRONMENT CURVE AT A PROJECTILE DIAMETER OF 1 CM.

BM13-8/21



EFFECT OF MISSION DURATION ON PROJECTILE DIAMETER



SAFETY

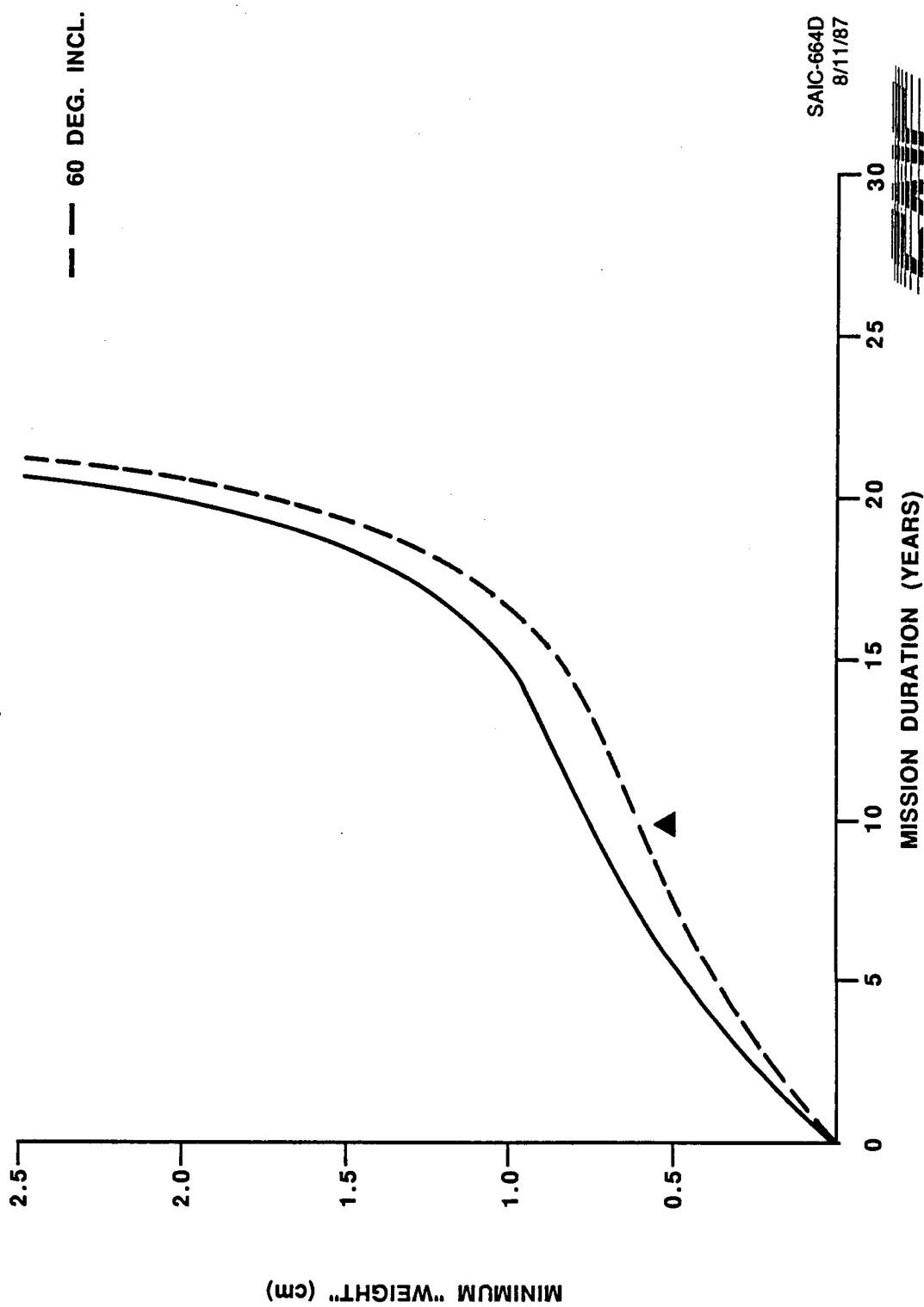
SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION
MISSIONS: BOEING PREDICTOR

SHOWN IS THE EFFECT OF MISSION DURATION ON OPTIMAL DESIGN FOR THE BOEING PREDICTOR FOR 30 AND 60 DEGREE INCLINATIONS. THE INFLECTION AT 15 YEARS, AND THE SHARP INCREASE IN SLOPE AT ABOUT 22 YEARS RAISES SERIOUS DESIGN QUESTIONS ABOUT LONG-DURATION MISSIONS FOR MISSION PLANNERS.

BM05-8/11

SACTM

**SERIOUS DESIGN PENALTIES ACCOMPANY LONG-DURATION
MISSIONS: BOEING PREDICTOR**



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8/11/87

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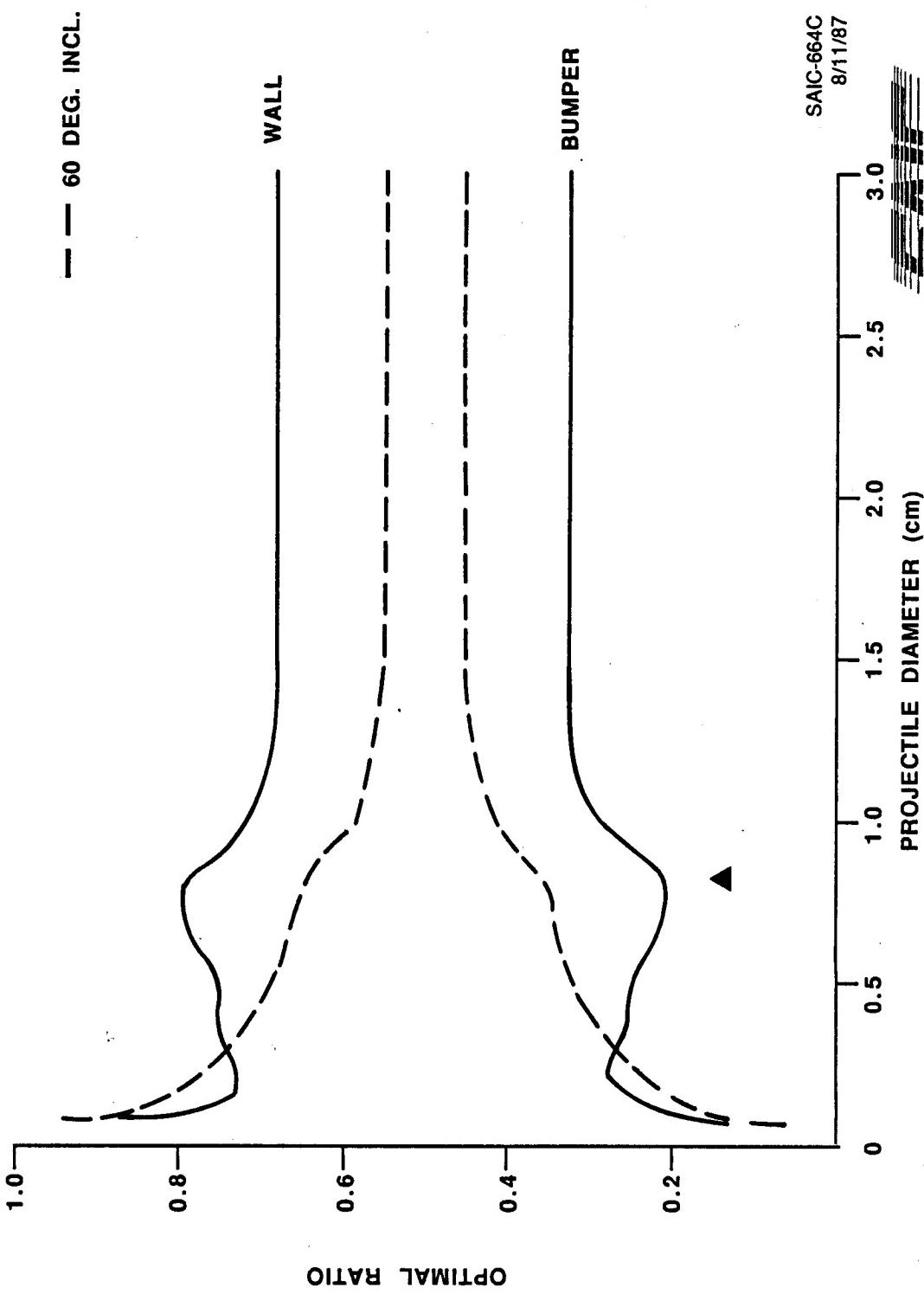
GP PROVIDES OPTIMAL DISTRIBUTION FOR BOEING PREDICTOR

THE OPTIMAL RATIO AS A FUNCTION OF PROJECTILE DIAMETER FOR THE BOEING PREDICTOR IS SHOWN FOR 30 AND 60 DEGREE INCLINATIONS. THIS IS THE RATIO OF OPTIMAL BUMPER (WALL) THICKNESS TO TOTAL OPTIMAL THICKNESS, AND IS QUITE NONLINEAR (AND NONCONSTANT). THIS NONLINEARITY HAS TO DO WITH THE INTERACTION OF THE MODIFIED BURCH AND WILKINSON PREDICTORS. NOTE THAT A 60 DEGREE INCLINATION TENDS TO EVEN OUT THE THICKNESS DISTRIBUTION BETWEEN BUMPER AND WALL, EXCEPT FOR SMALL PARTICLE DIAMETERS.

BM06-8/11



**GP PROVIDES OPTIMAL DISTRIBUTION
FOR BOEING PREDICTOR**



DESIGNER'S COST EXCURSION

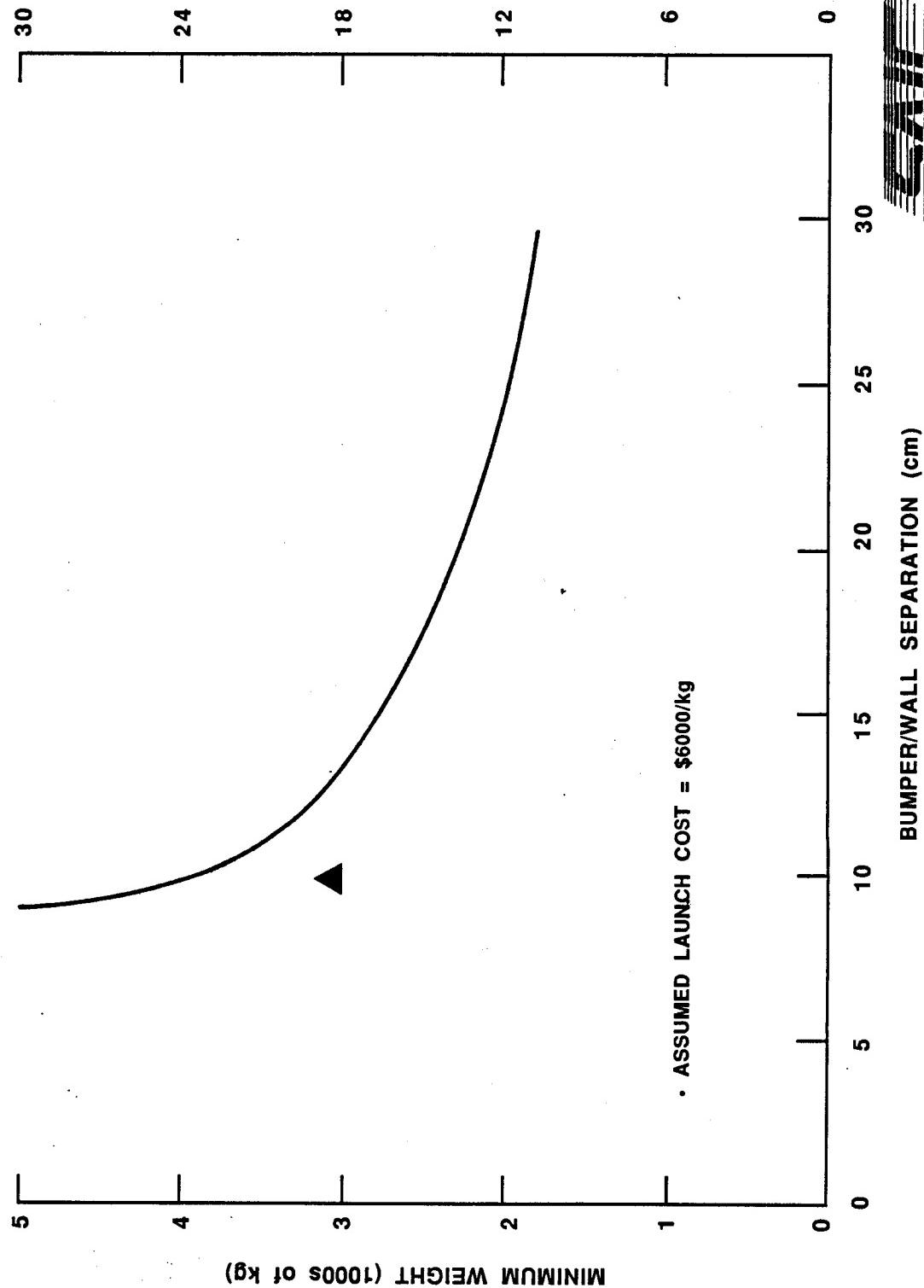
SHOWN IS THE EFFECT OF BUMPER/WALL SEPARATION ON CORE MODULE CONFIGURATION WEIGHT AND LAUNCH COST FOR THE BOEING PREDICTOR. THE ASSUMED LAUNCH COST IS \$6000/KG. BASED ON THIS ASSUMPTION, A SAVINGS OF ROUGHLY \$7M (30%) IN LAUNCH COST IS INDUCED BY AN INCREASE IN SEPARATION FROM 10 TO 15 CM.

BM19-8/21



DESIGNER'S COST EXCURSION

LAUNCH COST (millions of 1987 dollars)



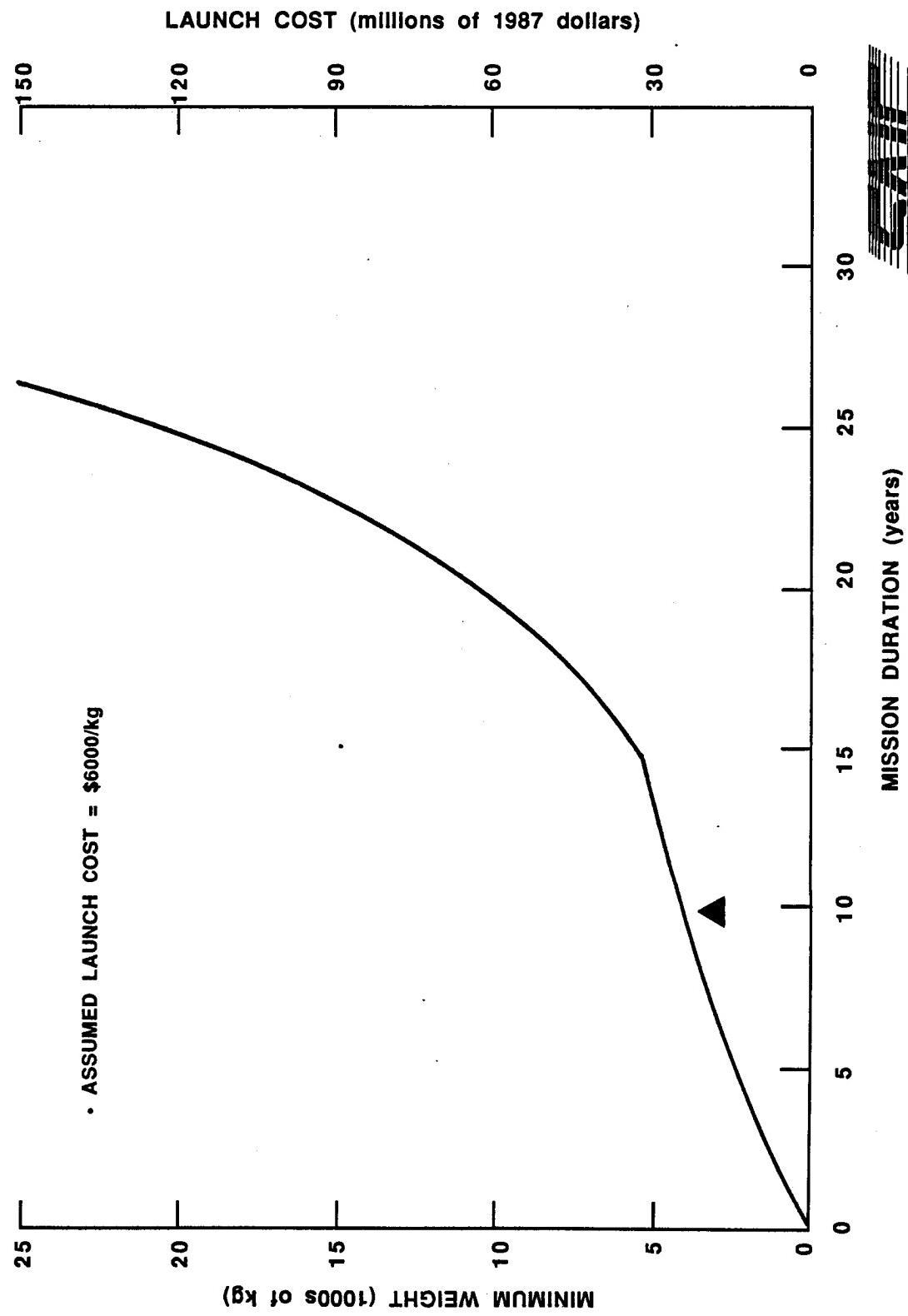
MISSION PLANNER'S COST EXCURSION

THE EFFECT OF MISSION DURATION ON CORE MODULE CONFIGURATION WEIGHT AND LAUNCH COST IS SHOWN FOR THE BOEING PREDICTOR. THE ASSUMED LAUNCH COST IS \$6000/KG. BASED ON THIS ASSUMPTION, AN INCREASE IN LAUNCH COST OF \$37M (163%) IS INDUCED BY INCREASING THE MISSION DURATION FROM 10 TO 20 YEARS.

BM20-8/21



MISSION PLANNER'S COST EXCURSION



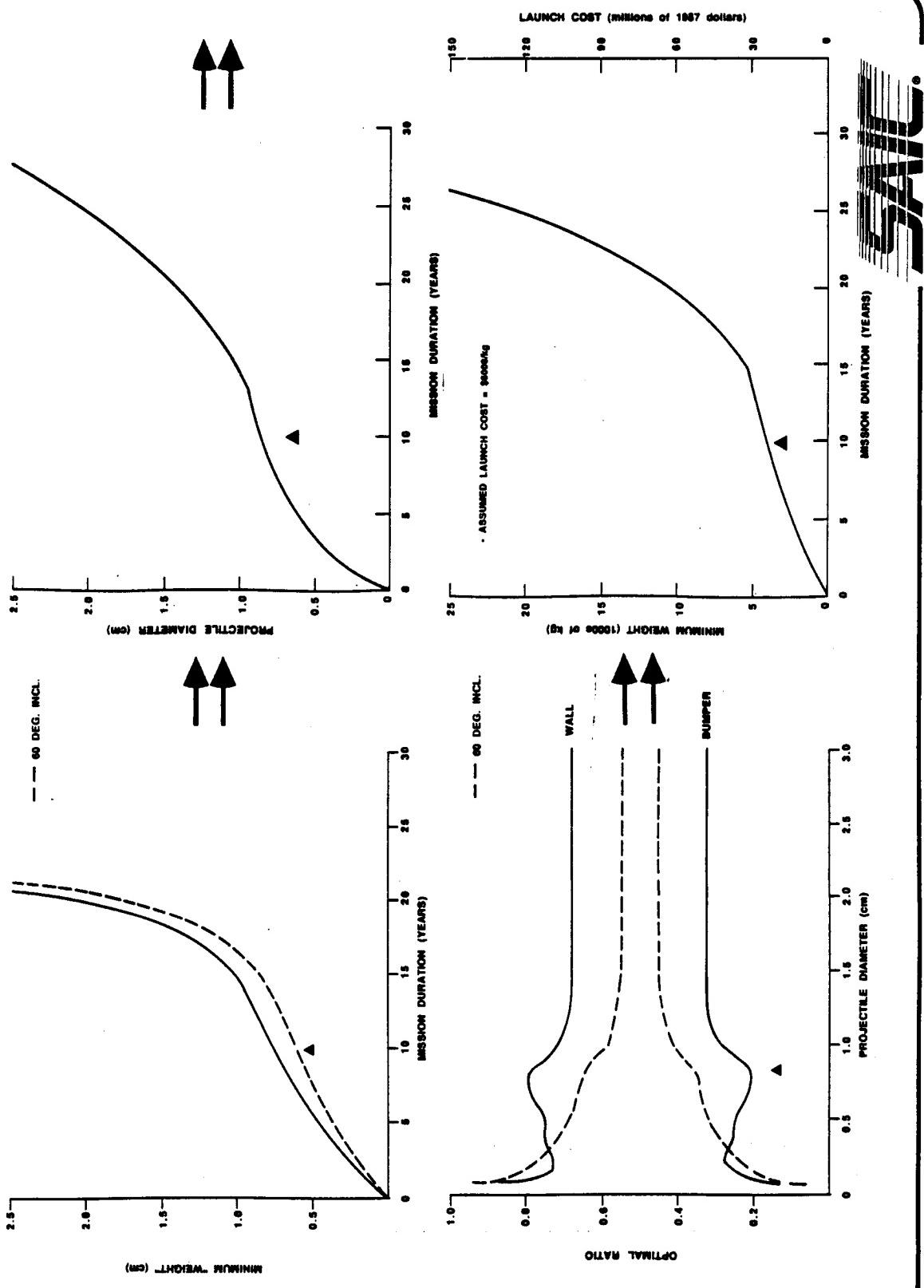
DETERMINING THE OPTIMAL PARAMETERS

AN EXAMPLE FOR DETERMINING THE OPTIMAL DESIGN PARAMETERS FOR THE VELOCITY-INTEGRATED BOEING PREDICTOR IS SHOWN. STARTING IN THE UPPER LEFT-HAND CORNER, IT IS DETERMINED THAT THE SUM OF THE MINIMUM BUMPER AND WALL THICKNESSES FOR A 10-YEAR MISSION (AND 30 DEGREE ORBITAL) INCLINATION IS ROUGHLY 0.75 CM. PROCEEDING TO THE RIGHT, ONE DETERMINES THE CRITICAL PROJECTILE DIAMETER TO BE APPROXIMATELY 0.85 CM. THIS CORRESPONDS TO AN OPTIMAL DISTRIBUTION OF 20% BUMPER, 80% WALL IN THE LOWER LEFT-HAND CORNER. THUS, THE OPTIMAL DESIGN THICKNESSES ARE DETERMINED TO BE ROUGHLY 0.15 CM FOR THE BUMPER, AND 0.60 CM FOR THE WALL. FINALLY, THE ACTUAL WEIGHT OF APPROXIMATELY 40000Kg AND COST OF ROUGHLY \$24M ARE DETERMINED FROM THE LOWER RIGHT-HAND CHART.

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DETERMINING THE OPTIMAL PARAMETERS



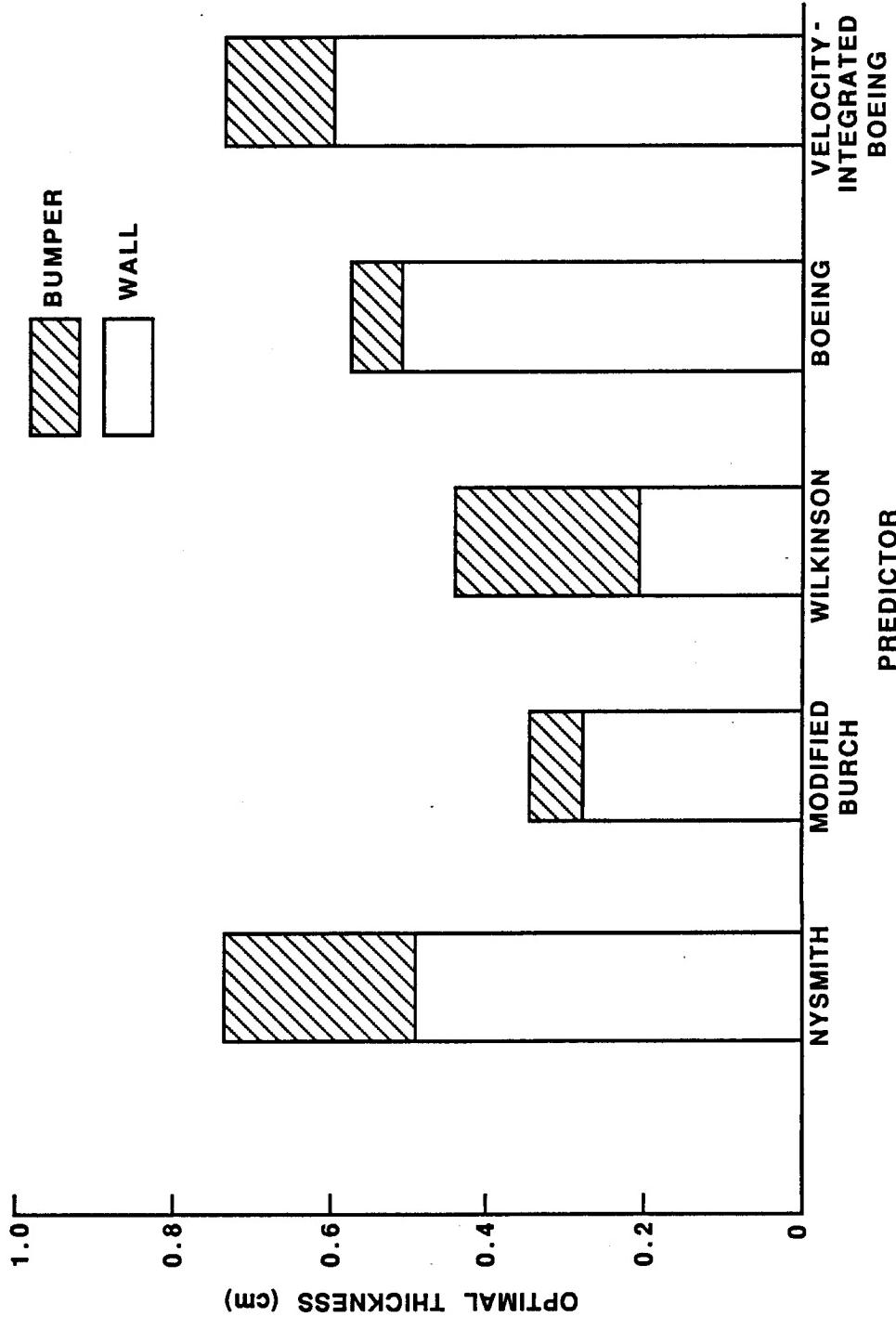
SUMMARY OF PREDICTOR RESULTS

SHOWN ARE THE OPTIMAL THICKNESSES FOR THE BASELINE PARAMETERS FOR EACH OF THE FIVE PREDICTORS INVESTIGATED IN THIS STUDY. IT IS INTERESTING TO NOTE THE DIVERSITY OF TOTAL THICKNESSES AND THICKNESS DISTRIBUTIONS FOR THESE CASES. NOTE ALSO THAT THE NYSMITH AND VELOCITY-INTEGRATED BOEING PREDICTORS BOTH ACHIEVE THE SAME TOTAL THICKNESSES, ALTHOUGH IN DIFFERENT PROPORTIONS.

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SUMMARY OF PREDICTOR RESULTS



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SECTION VII CONCLUSIONS

GEOMETRIC PROGRAMMING CONCLUSIONS

- GEOMETRIC PROGRAMMING (GP) IS SUPERIOR TO THE EXTREMA THEOREM (ET) FOR THOSE IMPACT PROBLEMS WHERE BOTH METHODS ARE APPLICABLE
- THIS SUPERIORITY INCREASES WITH INCREASING DESIGN COMPLEXITY
- REDUCTION OF THE GEOMETRIC PROGRAMMING PROBLEM FROM 5 DEGREES-OF-DIFFICULTY TO 2 RESULTS IN NEGIGIBLE DESIGN ERROR (PROVIDED BUMPER AND WALL THICKNESSES REMAIN SMALL IN COMPARISON TO MODULE RADIUS)
- OPTIMAL DESIGN DETERMINED FROM SPECIFIC MODULE CONFIGURATION IS NO DIFFERENT THAN FROM IDEALIZED SCENARIO.
- GEOMETRIC PROGRAMMING APPLIES TO NONLINEAR, FUNCTIONAL, PIECEWISE CONTINUOUS (E.G., WILKINSON) PREDICTORS IN POSYNOMIAL FORM
- SINCE IMPACT PREDICTOR INDEPENDENT VARIABLES ARE INHERENTLY POSITIVE-VALUED, THE ONLY POTENTIAL DOWNFALL FOR GEOMETRIC PROGRAMMING IS NEGATIVE COEFFICIENTS.
- THE BURCH PREDICTOR IS EASILY MODIFIED TO SATISFY THE POSYNOMIAL REQUIREMENT
- THE PEN4 PREDICTOR MAY NOT BE EASILY MODIFIED TO SATISFY THE POSYNOMIAL REQUIREMENT.



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SECTION VII CONCLUSIONS (CONT'D)

NYSMITH PREDICTOR CONCLUSIONS

- THE NYSMITH PREDICTOR HAS A THIRD INEQUALITY CONSTRAINT WHICH LIMITS ITS USAGE.
- THE COMPUTER SOLUTION REGION FOR THE NYSMITH PREDICTOR IS NARROW ENOUGH (FOR MOST PROBLEMS) TO BE APPROXIMATED ANALYTICALLY.
- THE NYSMITH PREDICTOR IMPLIES AN OPTIMAL THICKNESS DISTRIBUTION OF 35% BUMPER AND 65% WALL.
- THE NYSMITH PREDICTOR REQUIRES OPTIMAL BALLISTIC LIMIT THICKNESSES ROUGHLY 1.5 TIMES CURRENT DESIGN (FOR THE BASELINE DESIGN PARAMETERS)
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN FOR THE CORE MODULE CONFIGURATION.
- INCREASING THE BASELINE P_0 HEAVILY TAXES THE DESIGN.
 - A 50% INCREASE IN THE BASELINE BUMPER/WALL SEPARATION PROVIDES A 30% DECREASE IN THE TOTAL DESIGN THICKNESS.
- THE NYSMITH PREDICTOR SHOWS LITTLE DESIGN SENSITIVITY TO PROJECTILE VELOCITY.
- DESIGN IS HIGHLY SENSITIVE TO MISSION DURATION.



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SECTION VII CONCLUSIONS (CONT'D)

BOEING SUBPREDICTOR CONCLUSIONS

- THE PEN4 PREDICTOR SHOWS NO DEPENDENCY ON BUMPER/WALL SEPARATION
- THE PEN4 PREDICTOR IS NOT VALID FOR VELOCITIES ABOVE ROUGHLY 2.8 KM/SEC.
- ONE LOCAL OPTIMAL DESIGN DISTRIBUTION FOR THE PEN4 PREDICTOR IS 100% BUMPER, 0% WALL
- THE BURCH PREDICTOR SHOWS NO DEPENDENCY ON PROJECTILE OR WALL MATERIAL PROPERTIES
- THE MODIFIED BURCH PREDICTOR APPROXIMATES THE BURCH MODEL WELL
- THE MODIFIED BURCH MINIMUM "WEIGHT" IS INVERSELY PROPORTIONAL TO PROJECTILE VELOCITY
- THE WILKINSON PREDICTOR IS A PIECEWISE CONTINUOUS MODEL
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN FOR THE MODIFIED BURCH AND WILKINSON PREDICTORS
- THE WILKINSON PREDICTOR SHOWS MORE SENSITIVITY TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, MISSION RISK, AND MISSION DURATION THAN THE MODIFIED BURCH PREDICTOR
- OPTIMAL RATIOS ARE FAIRLY CONSTANT FOR ALL 3 BOEING SUBPREDICTORS



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SECTION VII CONCLUSIONS (CONT'D)

BOEING PREDICTOR CONCLUSIONS

- THE BOEING PREDICTOR IS A COMPLEX PIECEWISE CONTINUOUS PREDICTOR
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES THE DESIGN FOR THE BOEING PREDICTOR
- THE OPTIMAL DESIGN AS A FUNCTION OF PROJECTILE VELOCITY IS NOT MONOTONIC
- THE BOEING PREDICTOR SHOWS SHARP SENSITIVITIES TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, ACCEPTABLE MISSION RISK AND DURATION
- THE OPTIMAL RATIO FOR THE BOEING PREDICTOR IS ALSO NOT MONOTONIC AND IS FAIRLY SENSITIVE TO SMALL PROJECTILE DIAMETERS



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SECTION VII CONCLUSIONS (CONT'D)

VELOCITY-INTEGRATED BOEING PREDICTOR CONCLUSIONS

- UNDER THESE ASSUMPTIONS, A 60 DEGREE ORBITAL INCLINATION IS PREFERABLE TO A 30 DEGREE ONE FOR THE BOEING PREDICTOR
- THE DEBRIS ENVIRONMENT CLEARLY DRIVES DESIGN
- THIS PREDICTOR SHOWS STRONG SENSITIVITIES TO BUMPER/WALL SEPARATION, PROJECTILE DIAMETER, ACCEPTABLE MISSION RISK, AND DURATION
- THE OPTIMAL RATIO FOR THE VELOCITY-INTEGRATED PREDICTOR IS MONOTONIC FOR A 60 DEGREE ORBITAL INCLINATION, BUT NOT FOR A 30 DEGREE ONE

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SECTION VIII RECOMMENDATIONS

- EVALUATION OF BURCH, BOEING, AND VELOCITY-INTEGRATED BOEING PREDICTORS FOR NON-NORMAL IMPACTS
- COMPARISON OF RESULTS WITH BOEING'S BUMPER CODE
- FULL DESIGN TRADE EVALUATIONS FOR MADDEN, RICHARDSON, AND OTHER AVAILABLE PREDICTORS
- PREDICTOR/TEST DATA CORRELATION
- DESIGN GENERALIZATION TO INCLUDE CONSTRAINTS RELATED TO PRESSURE, THERMAL, STRESS, RADIATION, CONTAMINATION, AND OTHER EFFECTS AS APPLICABLE
- APPLICATION OF THIS DESIGN METHODOLOGY TO SPACE STATION COMPONENTS OTHER THAN CORE MODULE CONFIGURATION (E.G., TANKS, OMV, OTV)
- APPLICATION OF THIS DESIGN METHODOLOGY TO OTHER PROGRAMS (E.G., DEEP SPACE PROBES, PLANETARY MISSIONS, TRANSFER VEHICLES, SPACEPORTS)



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SECTION VIII RECOMMENDATIONS (CONT'D)

- COMPUTER CODE DEVELOPMENT TO ANALYZE GENERIC PREDICTORS
- EVALUATION OF EFFECT OF EVOLVING SPACE DEBRIS ENVIRONMENT ON DESIGN
- EVALUATION OF EFFECT OF CHANGES IN CMC DESIGN ON OPTIMAL THICKNESSES
- COMPUTER PLOTTING POST-PROCESSOR FOR RAPID DISPLAY OF DESIGNER TRADEOFFS

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SECTION IX

REFERENCES

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SURVIVABILITY AND PREDICTOR REFERENCES

1. SUSKO, M., "A REVIEW OF MICROMeteorID FLUX MEASUREMENTS AND MODELS FOR LOW ORBITAL ALTITUDES OF THE SPACE STATION", NASA TM-86466, GEORGE C. MARSHALL SPACE FLIGHT CENTER, SEPTEMBER 1984.
2. KESSLER, D., "ORBITAL DEBRIS ENVIRONMENT FOR SPACE STATION," JSC-20001.
3. NYSMITH, C.R., "AN EXPERIMENTAL IMPACT INVESTIGATION OF ALUMINUM DOUBLE-SHEET STRUCTURES", AIAA HYPERVELOCITY IMPACT CONFERENCE, CINCINNATI, OHIO, APRIL 30-MAY 2, 1969, AIAA PAPER NO. 69-375.

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SURVIVABILITY AND PREDICTOR REFERENCES
(CONTINUED)

4. WILKINSON, J.P.D., "A PENETRATION CRITERION FOR DOUBLE-WALLED STRUCTURES SUBJECT TO METEOROID IMPACT," AIAA JOURNAL, VOL. 7, NO. 10, OCTOBER, 1969.
5. CORONADO, A.R., GIBBINS, M.N., WRIGHT, M.A., AND STERN, P.H., "SPACE STATION INTEGRATED WALL DESIGN AND PENETRATION DAMAGE CONTROL," BOEING AEROSPACE COMPANY FINAL REPORT, CONTRACT NAS8-36426, JULY 1987.
6. COUR-PALAIS, B., "METEOROID ENVIRONMENT MODEL - 1969 (NEAR-EARTH TO LUNAR SURFACE)", NASA SP-8013, MARCH 1969.

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OPTIMIZATION REFERENCES

1. GOTTERIED, B.S., AND WEISMAN, J., INTRODUCTION TO OPTIMIZATION THEORY, PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, NEW JERSEY, 1973.
2. AVRIEL, M., ADVANCES IN GEOMETRIC PROGRAMMING, PLENUM PRESS, NEW YORK, 1980.
3. WHITTLE, P., OPTIMIZATION UNDER CONSTRAINTS, JOHN WILEY & SONS, LTD., 1971.
4. WILDE, D.J., GLOBALLY OPTIMAL DESIGN, JOHN WILEY & SONS, INC., 1978.
5. AVRIEL, M., NONLINEAR PROGRAMMING ANALYSIS AND METHODS, PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, NEW JERSEY, 1976.

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OPTIMIZATION REFERENCES
(CONTINUED)

6. MCCORMICK, G.P., NONLINEAR PROGRAMMING THEORY, ALGORITHMS, AND APPLICATIONS, JOHN WILEY & SONS, INC., 1983.
7. VANDERPLAATS, G.N., NUMERICAL OPTIMIZATION TECHNIQUES FOR ENGINEERING DESIGN WITH APPLICATIONS, McGRAW-HILL, INC., 1984.
8. PRICE, D. MARVIN, UNPUBLISHED MASTER'S THESIS AND TECHNICAL DOCUMENTATION ON THE SUBJECT OF GEOMETRIC PROGRAMMING.

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SECTION X

APPENDICES

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A. MATHEMATICS

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GP APPLIED TO NYSMITH

Consider the Nysmith Equation:

$$t_2 = 5.08V^{.278}d^{2.92}/(t_1^{0.528}h^{1.39}) ,$$

with inequality constraints

$$t_1/d \leq 0.5 , t_2/d \leq 1.0$$

Note that if

$$d > 0.24hV^{-0.2} , \text{ then}$$

$$\frac{t_1}{d} \leq 0.5 \Rightarrow$$

$$\frac{t_2}{d} > 5.08V^{.278}(0.24hV^{-0.2})^{1.39}/[(0.5)^{.528}h^{1.39}] \text{ or ,}$$

$$\frac{t_2}{d} > 1.0$$

Therefore, the third inequality constraint of Nysmith may be written:

$$d \leq 0.24hV^{-0.2}$$

Letting the idealized "weight" be denoted by w , one has:

$$w = t_1 + t_2$$

Substituting Nysmith, one has:

$$w = t_1 + 5.08V^{.278}d^{2.92}/(t_1^{0.528}h^{1.39}) ,$$

with inequality constraints:

$$\frac{2t_1}{d} \leq 1.0 , 5.08V^{.278}d^{1.92}/(t_1^{0.528}h^{1.39}) \leq 1.0$$



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A. Unconstrained Optimization

The dual GP problem may be written:

maximize: $v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2}$

subject to: $\delta_1 + \delta_2 = 1$

$$\delta_1 - 0.528\delta_2 = 0$$

where: $c_1 = 5.08V^{.278}d^{2.92}/h^{1.39}$

This is easily solved, giving:

$$\delta_1 = 0.35, \quad \delta_2 = 0.65,$$

$$w_0 = 5.52V^{.18}d^{1.91}/h^{0.91}$$

is the minimum "weight".

$$t_{1_0} = 1.93V^{.18}d^{1.91}/h^{0.91}$$

is the optimal bumper thickness, and

$$t_{2_0} = 3.59V^{.18}d^{1.91}/h^{0.91}$$

is the optimal wall thickness.

Note that the optimal ratios are given by:

$$\frac{t_{1_0}}{t_{1_0} + t_{2_0}} = 0.35 = \delta_1, \quad \frac{t_{2_0}}{t_{1_0} + t_{2_0}} = 0.65 = \delta_2$$

Furthermore, this analytic solution is valid for

$$d \leq 0.23hV^{-0.2} \quad \text{Why?}$$

$$h \geq 4.35dV^{0.2} \Rightarrow t_{1_0} \leq 1.93V^{.18}d^{1.91}(4.35dV^{0.2})^{-0.91} \quad \text{or}$$

$$t_{1_0} \leq 0.5d, \quad \text{as desired. Also,}$$

$$t_{2_0} = 1.86t_{1_0} < d, \quad \text{as required.}$$



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Thus the constrained problem need only be solved for

$$0.23hV^{-0.2} \leq d \leq 0.24hV^{-0.2}$$

B. Constrained Optimization

The constrained dual GP problem may be written:

maximize: $v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2} (c_3)^{\delta_{11}'} (c_4)^{\delta_{12}'}$

subject to: $\delta_1 + \delta_2 = 1$

$$\delta_1 - 0.528\delta_2 + \delta_{11}' - 0.528\delta_{12}' = 0$$

where: c_1 is defined as in part A

$$c_2 = c_1/d$$

$$c_3 = 2/d$$

This is a 2 degree-of-difficulty problem, since there are 2 equations and 4 unknowns. It is solved numerically.



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DERIVATION OF CORE MODULE CONFIGURATION WEIGHT

Let: r_{12} = radius of a core module

$$r_{22} = r_{12} + t_2$$

$$r_{11} = r_{22} + h$$

$$r_{21} = r_{11} + t_1$$

$$L = \text{core module length}$$

Then,

$$w = \pi L [\rho_1(r_{21}^2 - r_{11}^2) + \rho_2(r_{22}^2 - r_{12}^2)]$$

is the total core module weight.



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GP APPLIED TO THE CMC WEIGHT FUNCTION

Let: $r_{12} = 210.8 \text{ cm}$

$L = 1356.7 \text{ cm}$

$\rho_1 = \rho_2 = 2.81 \text{ gm/cm}^3$

Applying the Nysmith equation, one has:

$$w_{CMC} = 12t_1^2 + c_1t_1 + 122c_2t_1^{0.472} + 25700c_2t_1^{-0.528} + 310c_2^2t_1^{-1.06}$$

where:

$$c_1 = 5059 + 24h, \text{ and}$$

$$c_2 = V^{.278}d^{2.92}/h^{1.39}$$

The chosen approximate weight is given by:

$$w_{CMC_{approx}} = c_1t_1 + 25700c_2t_1^{-0.528}$$

The unconstrained GP problem is then:

maximize:

$$v(\delta) = (c_1/\delta_1)^{\delta_1} \left(\frac{25700c_2}{\delta_2} \right)^{\delta_2}$$

subject to: $\delta_1 + \delta_2 = 1$

$$\delta_1 - .528\delta_2 = 0$$

This is easily solved yielding:

$$\delta_1 = 0.346, \quad \delta_2 = 0.654$$



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$$w_0 = 1459 c_1^{0.346} c_2^{0.654}$$

$$t_{1_0} = \frac{\delta_1 w_0}{c_1} = 505 \left(\frac{c_2}{c_1} \right)^{0.654}$$

$$t_{2_0} = 1.89 t_{1_0} = 954 \left(\frac{c_2}{c_1} \right)^{0.654}$$



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GP APPLIED TO WILKINSON

Recall that:

$$\frac{D\rho_p}{\rho_1 t_1} \leq 1 \Rightarrow t_2 = 0.364 D^3 \rho_p V_N / (L_2 S^2 \rho_2) \text{ and ,}$$

$$\frac{D\rho_p}{\rho_1 t_1} > 1 \Rightarrow t_2 = 0.364 D^4 \rho_p^2 V_N / (L_2 S^2 \rho_1 t_1 \rho_2)$$

Consider the case where:

$$\frac{D\rho_p}{\rho_1 t_1} > 1$$

Then, $w = t_1 + c_1 t_1^{-1}$ is the idealized weight.

Where:

$$c_1 = 0.364 D^4 \rho_p^2 V_N / (L_2 S^2 \rho_1 \rho_2)$$

The dual GP problem may be written:

maximize: $v(\delta) = (1/\delta_1)^{\delta_1} (c_1/\delta_2)^{\delta_2}$

subject to: $\delta_1 + \delta_2 = 1$

$$\delta_1 - \delta_2 = 0$$

Thus, $\delta_1 = \delta_2 = 1/2$, and

$$w_0 = 1.207 \frac{D^2 \rho_p}{S} \left(\frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2}$$

$$t_{1_0} = t_{2_0} = 0.604 \frac{D^2 \rho_p}{S} \left(\frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2}$$



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Thus, the procedure is the following:

1) Determine t_{1_0} , t_{2_0} from the above equation.

2) Compute $\frac{D\rho_p}{\rho_1 t_{1_0}}$.

3) If $\frac{D\rho_p}{\rho_1 t_{1_0}} > 1$, then quit. Optimal design is (t_{1_0}, t_{2_0}) .

4) If $\frac{D\rho_p}{\rho_1 t_{1_0}} \leq 1$, optimal design is $(t_{1_0}, t_{2_0} \left(\frac{D\rho_p}{\rho_1 t_{1_0}} \right))$.

Optimal Ratios for Wilkinson

Recall that the optimal thickness distribution between bumper and wall is equal unless:

$$\frac{D\rho_p}{\rho_1 t_{1_0}} \leq 1 \text{ , or } t_{1_0} \geq \frac{D\rho_p}{\rho_1}$$

This implies:

$$0.604 \frac{D^2 \rho_p}{S} \left(\frac{V_N}{L_2 \rho_1 \rho_2} \right)^{1/2} \geq \frac{D \rho_p}{\rho_1} \text{ , or}$$

$$D \geq 1.66 s \left(\frac{L_2 \rho_2}{V_N \rho_1} \right)^{1/2}$$



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GP APPLIED TO MODIFIED BURCH

Recall the Modified Burch Predictor:

$$t_2 = \bar{C} \bar{K} , \text{ where}$$

$$\bar{C} = \left(\frac{D}{N} \right)^{1.71} \left(\frac{C}{V} \right)^{2.29} / S^{0.71} , \text{ and}$$

$$\bar{K} = 2.8(t_1/D)^{0.57} + 1.58(t_1/D)^{-0.57}$$

Thus,

$$w = t_1 + 2.8\bar{C}D^{-0.57}t_1^{0.57} + 1.58\bar{C}D^{0.57}t_1^{-0.57} \text{ is the idealized weight.}$$

Thus, the GP dual problem may be written:

Maximize:

$$v(\delta) = \left(\frac{1}{\delta_1} \right)^{\delta_1} \left(\frac{2.8\bar{C}D^{-0.57}}{\delta_2} \right)^{\delta_2} \left(\frac{1.58\bar{C}D^{0.57}}{\delta_3} \right)^{\delta_3}$$

Subject to:

$$\delta_1 + 0.57\delta_2 - 0.57\delta_3 = 0 , \text{ and}$$

$$\delta_1 + \delta_2 + \delta_3 = 1$$

Thus, we have:

$$\delta_2 = 2.33(1 - 1.57\delta_3) , \quad \delta_1 = 1.33(2\delta_3 - 1) ,$$

and since $\delta_1 > 0$, $\delta_2 > 0$, we have $0.5 < \delta_3 < 0.64$.

This is a one degree-of-difficulty problem with the following procedure:

- 1) Vary δ_3 from 0.5 to 0.64 to find the max $v(\delta)$.
- 2) Using the corresponding δ_3 , solve for δ_1 , δ_2 .
- 3) Let $t_{1_0} = \delta_1(\max(v(\delta)))$.
- 4) Let $t_{2_0} = \max(v(\delta)) - t_{1_0}$.



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OPTIMAL DESIGN ALGORITHM FOR BOEING PREDICTOR

1. Compute optimal design for PEN4 Predictor, $\left(t_{1_{0_p}}, t_{2_{0_p}} \right)$.
2. Check against PEN4 constraint, $V \leq V_f \left[t_{1_{0_p}} / D \right] + 4000 ?$
3. If satisfied, the optimal design is $\left(t_{1_0}, t_{2_0} \right) = \left(t_{1_{0_p}}, t_{2_{0_p}} \right)$.
4. Else, compute optimal designs for Modified Burch, $\left(t_{1_{0_B}}, t_{2_{0_B}} \right)$, and Wilkinson, $\left(t_{1_{0_W}}, t_{2_{0_W}} \right)$ Predictors.
5. Compute Wilkinson wall induced by optimal Modified Burch bumper, $t_{2_W} \left(t_{1_{0_B}} \right)$.
6. Compute Burch wall induced by optimal Wilkinson bumper, $t_{2_B} \left(t_{1_{0_W}} \right)$.
7. Find $\left(t_{1_0}, t_{2_0} \right) = \min_{t_1 + t_2} \left[\left(t_{1_{0_B}}, \max \left(t_{2_{0_B}}, t_{2_W} \left(t_{1_{0_B}} \right) \right) \right), \left(t_{1_{0_W}}, \max \left(t_{2_{0_W}}, t_{2_B} \left(t_{1_{0_W}} \right) \right) \right) \right]$.



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B. COMPUTER CODES

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METEOR1

METEOR1 is the meteoroid environment model (see Survivability and Predictor Reference 1) used in the design of protective systems for spacecraft. It is used to define projectile mass/diameter as a preprocessor to IMPACT5 and its derivatives.

METEOR1 takes as inputs the spacecraft exposed surface area, the mission duration, probability of no penetration and altitude, and the particle density. METEOR1 accounts for Earth shielding and gravitational defocussing factors. The output is the critical projectile diameter. A sample input (MET.IN), output (MET.OUT) and program listing (METEOR1.LIS) follow.

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1 !NO. OF CASES
400. !SURFACE AREA IN SQ. METERS
10. !DURATION IN YEARS
.97 !PROB. OF NO PENETRATION
500. !ALT. IN KM
.5 !DENSITY IN GM/CUBIC CM

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INPUT

SURFACE AREA IN SQUARE METERS = 400.0000
MISSION DURATION IN YEARS = 10.00000
PROB. OF NO PENETRATION = 0.9700000
ALTITUDE IN KILOMETERS = 500.0000
PROJ. DENSITY IN GM/CUBIC CM = 0.5000000

OUTPUT

DIAM= 0.4614225

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VAX FORTRAN
SAI_USRDISK

```
0001 OPEN(UNIT=9,TYPE='OLD',ACCESS='SEQUENTIAL',NAME='MET.IN')
0002 OPEN(UNIT=10,TYPE='NEW',ACCESS='SEQUENTIAL',NAME='MET.OUT')
0003 READ(9,*)NCASES
0004 DO 10 I=1,NCASES
0005     READ(9,*)SA
0006     READ(9,*)T
0007     READ(9,*)PO
0008     READ(9,*)ALT
0009     READ(9,*)DENS
0010     WRITE (10,*)'           INPUT'
0011     WRITE (10,*)'
0012     WRITE(10,*)'           SURFACE AREA IN SQUARE METERS = ',SA
0013     WRITE(10,*)'           MISSION DURATION IN YEARS = ',T
0014     WRITE(10,*)'           PROB. OF NO PENETRATION = ',PO
0015     WRITE(10,*)'           ALTITUDE IN KILOMETERS = ',ALT
0016     WRITE(10,*)'           PROJ. DENSITY IN GM/CUBIC CM = ',DENS
0017     WRITE (10,*)'
0018     WRITE (10,*)'           OUTPUT'
0019     WRITE (10,*)'
0020     T=31536000.*T
0021     FLUX=-1.* ALOG(PO)/(SA*T)
0022     RA=6371./(6371.+ALT)
0023     GE=.568+.432*RA
0024     THETA=ATAN(6371./SQRT(ALT*(ALT+2.*6371.)))
0025     S=(1.+COS(THETA))/2.
0026     FLUX=FLUX/(GE*S)
0027     F=ALOG10(FLUX)
0028     IF(F.GE.-4.403)THEN
0029         WRITE(10,*)'           MASS IS TOO SMALL'
0030         GO TO 10
0031     ENDIF
0032     IF(F.GT.-7.103.AND.F.LT.-4.403)THEN
0033         RAD=2.509-.25*(14.339+L)
0034         XM=10.**((-1.584+SQRT(RAD))/.125)
0035     ENDIF
0036     IF(F.LE.-7.103.AND.F.GE.-14.37)THEN
0037         XM=10.**((14.37+F)/-1.213)
0038     ENDIF
0039     IF(F.LT.-14.37)THEN
0040         WRITE(10,*)'           MASS IS TOO LARGE'
0041         GO TO 10
0042     ENDIF
0043     D=(1.91*XM/DENS)**.333
0044     WRITE(10,*)'           DIAM=' ,D
0045     CONTINUE
0046 END
```

10

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5/16

DEBRIS1

DEBRIS1 is the space debris environment model (see Survivability and Predictor Reference 2) in the design of protective systems for spacecraft. It is used to define projectile mass/diameter as a preprocessor to IMPACT5 and its derivatives.

DEBRIS1 takes as inputs the spacecraft projected debris area, the mission duration, probability of no penetration, and altitude (currently fixed at 500 Km). The output is the critical projectile diameter. A sample input (DEB.IN), output (DEB.OUT), and program listing (DEBRIS1.LIS) follow.

SALE

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1 !NO. OF CASES
574. !PROJECTED AREA IN SQ. METERS
10. !DURATION IN YEARS
.97 !PROB. OF NO PENETRATION

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SAIC

INPUT

PROJ. AREA IN SQUARE METERS = 574.0000
MISSION DURATION IN YEARS = 10.00000
PROB. OF NO PENETRATION = 0.9700000

OUTPUT

DIAM= 0.8446254

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SAIC

12-Aug-1987 13:52:31
12-Aug-1987 13:52:24

VAX FORTRAN
SAI_USRDISK

```
0001      OPEN(UNIT=9,TYPE='OLD',ACCESS='SEQUENTIAL',NAME='DEB.IN')
0002      OPEN(UNIT=10,TYPE='NEW',ACCESS='SEQUENTIAL',NAME='DEB.OUT')
0003      READ(9,*)NCASES
0004      DO 10 I=1,NCASES
0005          READ(9,*)AP
0006          READ(9,*)T
0007          READ(9,*)PO
0008          WRITE(10,*)'      INPUT'
0009          WRITE(10,*)'
0010          WRITE(10,*)'      PROJ. AREA IN SQUARE METERS = ',AP
0011          WRITE(10,*)'      MISSION DURATION IN YEARS = ',T
0012          WRITE(10,*)'      PROB. OF NO PENETRATION = ',PO
0013          WRITE(10,*)'
0014          WRITE(10,*)'      OUTPUT'
0015          WRITE(10,*)'
0016          FLUX=-1.* ALOG(PO)/(AP*T)
0017          F=ALOG10(FLUX)
0018          IF(F.GE.-5.46)THEN
0019              D=10.**((F+5.46)/-2.52)
0020          ENDIF
0021          IF(F.LE.-7.0)THEN
0022              D=10.**((F-21.67)/-10.32)
0023          ENDIF
0024          IF(F.LT.-5.46.AND.F.GT.-7.0)THEN
0025              D=10.**((5.46+F)/-.63)
0026          ENDIF
0027          WRITE(10,*)'      DIAM=',D
0028      10      CONTINUE
0029      END
```

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SAC

IMPACT5

IMPACT5 is a spacecraft protective systems design optimization code. IMPACT5 employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, Burch, and PEN4 predictors. Inputs vary depending on the predictor used, however, typical inputs include projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5 is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. Sample input (IMPACT5.IN), output (IMPACT5.OUT) and program listing (IMPACT5.LIS) follow.

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SAIC

6 !NUMBER OF CASES
1 !NYSMITH PREDICTOR
10. !PROJ. VELOCITY IN KM/SEC
0.84 !PROJ. DIAMETER IN CM
10. !BUMPER/WALL SEPARATION IN CM
2 !BOEING PREDICTOR
10. !PROJ. VELOCITY IN KM/SEC
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
2.81 !WALL DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0.401 !WALL MATERIAL CONSTANT
7344000. !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000. !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0. !IMPACT ANGLE FROM NORMAL
0.85 !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11 !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3 !MADDEN PREDICTOR
10. !PROJ. VELOCITY IN KM/SEC
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
2.81 !BUMPER/WALL DENSITY IN GM/CUBIC CM
4 !WILKINSON PREDICTOR
10. !PROJ. VELOCITY IN KM/SEC
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
2.81 !WALL DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0.401 !WALL MATERIAL CONSTANT
5 !BURCH PREDICTOR
10. !PROJ. VELOCITY IN KM/SEC
0.84 !PROJ. DIA. IN CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0. !IMPACT ANGLE FROM NORMAL
0.85 !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11 !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
6 !PEN4 PREDICTOR
1. !PROJ. VELOCITY IN KM/SEC
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
2.81 !WALL DENSITY IN GM/CUBIC CM
7344000. !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000. !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0. !IMPACT ANGLE FROM NORMAL

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SAC

NYSMITH

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2575910 CM
WALL THICKNESS = 0.4791193 CM
MIN. WEIGHT = 0.7367103 CM
CMC MIN. WEIGHT = 3799.036 KG

BOEING

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 9.2028841E-02CM
WALL THICKNESS = 0.4910776 CM
MIN. WEIGHT = 0.5831065 CM
CMC MIN. WEIGHT = 2978.630 KG

MADDEN

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.3788331 CM
WALL THICKNESS = 0.3788331 CM
MIN. WEIGHT = 0.7576661 CM
CMC MIN. WEIGHT = 3934.167 KG

WILKINSON

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.2128253 CM
WALL THICKNESS = 0.2128253 CM
MIN. WEIGHT = 0.4256506 CM
CMC MIN. WEIGHT = 2208.558 KG

MODIFIED BURCH

INPUT

PROJECTILE VELOCITY IN KM/SEC = 10.00000
PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 9.2028841E-02CM
WALL THICKNESS = 0.2539445 CM
MIN. WEIGHT = 0.3459734 CM
CMC MIN. WEIGHT = 1775.339 KG

PEN4

INPUT

PROJECTILE VELOCITY IN KM/SEC = 1.000000
PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00

OUTPUT

BUMPER THICKNESS = 2.1661645E-02CM

WALL THICKNESS = 0.0000000E+00CM
MIN. WEIGHT = 2.1661645E-02CM
CMC MIN. WEIGHT = 222.9546 KG

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SAIC

10-Aug-1987 11:29:15
10-Aug-1987 11:29:03

VAX FOR
SAI_USR

```
0001      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5.IN',ACCESS='SEQUENTIAL')
0002      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5.OUT',ACCESS='SEQUENTIAL')
0003      READ(10,*)NRUNS
0004      DO 10 I=1,NRUNS
0005          READ(10,*)NCODE
0006          IF(NCODE.EQ.1)GO TO 25
0007          IF(NCODE.EQ.2)GO TO 35
0008          IF(NCODE.EQ.3)GO TO 45
0009          IF(NCODE.EQ.4)GO TO 55
0010          IF(NCODE.EQ.5)GO TO 65
0011          IF(NCODE.EQ.6)GO TO 75
0012      25      READ(10,*)V
0013      READ(10,*)D
0014      READ(10,*)H
0015          WRITE(11,*)'      NYSMITH'
0016          WRITE(11,*)'
0017          WRITE(11,*)'      INPUT'
0018          WRITE(11,*)'
0019          WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
0020          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0021          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',H
0022          WRITE(11,*)'
0023          CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0024          WRITE(11,*)'      OUTPUT'
0025          WRITE(11,*)'
0026          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0027          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0028          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0029          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0030          WRITE(11,*)'
0031          WRITE(11,*)'
0032          WRITE(11,*)'
0033          GO TO 10
0034      35      READ(10,*)V
0035      READ(10,*)D
0036      READ(10,*)RHOP
0037      READ(10,*)RHO1
0038      READ(10,*)RHO2
0039      READ(10,*)S
0040      READ(10,*)XL2
0041      READ(10,*)SY1
0042      READ(10,*)SY2
0043      READ(10,*)THETA
0044      READ(10,*)XN
0045      READ(10,*)E1
0046          WRITE(11,*)'      BOEING'
0047          WRITE(11,*)'
0048          WRITE(11,*)'      INPUT'
0049          WRITE(11,*)'
0050          WRITE(11,*)'      PROJECTILE VELOCITY IN KM/SEC = ',V
0051          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0052          WRITE(11,*)'      PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0053          WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
0054          WRITE(11,*)'      WALL DENSITY IN GM/CUBIC CM = ',RHO2
0055          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
0056          WRITE(11,*)'      WALL MATERIAL CONSTANT = ',XL2
0057          WRITE(11,*)'      BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
```

```

0058      WRITE(11,*)' WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
0059      WRITE(11,*)' IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0060      WRITE(11,*)' NUMBER OF PLATES TO PENETRATE AFTER FIRST',
0061      &           ' BUMPER = ',XN
0062      WRITE(11,*)' BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
0063      &           ' SEC = ',E1
0064      WRITE(11,*)'
0065      CALL BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
0066      &           XN,E1,T1,T2,WT,WTCMC)
0067      WRITE(11,*)' OUTPUT'
0068      WRITE(11,*)'
0069      WRITE(11,*)' BUMPER THICKNESS = ',T1,'CM'
0070      WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
0071      WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
0072      WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
0073      WRITE(11,*)'
0074      WRITE(11,*)'
0075      WRITE(11,*)'
0076      GO TO 10
0077      45    READ(10,*)V
0078      READ(10,*)D
0079      READ(10,*)RHOP
0080      READ(10,*)S
0081      READ(10,*)RHO
0082      WRITE(11,*)' MADDEN'
0083      WRITE(11,*)'
0084      WRITE(11,*)' INPUT'
0085      WRITE(11,*)'
0086      WRITE(11,*)' PROJECTILE VELOCITY IN KM/SEC = ',V
0087      WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
0088      WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0089      WRITE(11,*)' BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
0090      WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
0091      WRITE(11,*)'
0092      CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0093      WRITE(11,*)' OUTPUT'
0094      WRITE(11,*)'
0095      WRITE(11,*)' BUMPER THICKNESS = ',T1,'CM'
0096      WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
0097      WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
0098      WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
0099      WRITE(11,*)'
0100      WRITE(11,*)'
0101      WRITE(11,*)'
0102      GO TO 10
0103      55    READ(10,*)V
0104      READ(10,*)D
0105      READ(10,*)RHOP
0106      READ(10,*)RHO1
0107      READ(10,*)RHO2
0108      READ(10,*)S
0109      READ(10,*)XL2
0110      WRITE(11,*)' WILKINSON'
0111      WRITE(11,*)'
0112      WRITE(11,*)' INPUT'
0113      WRITE(11,*)'
0114      WRITE(11,*)' PROJECTILE VELOCITY IN KM/SEC = ',V

```

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IMPACT5\$MAIN

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VAX FOR

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SAI_USR

```
0115      WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
0116      WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0117      WRITE(11,*)' BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0118      WRITE(11,*)' WALL DENSITY IN GM/CUBIC CM = ',RH02
0119      WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
0120      WRITE(11,*)' WALL MATERIAL CONSTANT = ',XL2
0121      WRITE(11,*)'
0122      CALL WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,
0123      &           T1,T2,WT,WTCMC)
0124      WRITE(11,*)' OUTPUT'
0125      WRITE(11,*)'
0126      WRITE(11,*)' BUMPER THICKNESS = ',T1,'CM'
0127      WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
0128      WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
0129      WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
0130      WRITE(11,*)'
0131      WRITE(11,*)'
0132      WRITE(11,*)'
0133      GO TO 10
0134      65      READ(10,*)V
0135      READ(10,*)D
0136      READ(10,*)RH01
0137      READ(10,*)S
0138      READ(10,*)THETA
0139      READ(10,*)XN
0140      READ(10,*)E1
0141      ***** MODIFIED BURCH *****
0142      WRITE(11,*)' MODIFIED BURCH'
0143      WRITE(11,*)'
0144      WRITE(11,*)' INPUT'
0145      WRITE(11,*)'
0146      WRITE(11,*)' PROJECTILE VELOCITY IN KM/SEC = ',V
0147      WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
0148      WRITE(11,*)' BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0149      WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
0150      WRITE(11,*)' IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0151      WRITE(11,*)' NUMBER OF PLATES TO PENETRATE AFTER FIRST',
0152      &           ' BUMPER = ',XN
0153      &           WRITE(11,*)' BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
0154      &           SEC = ',E1
0155      WRITE(11,*)'
0156      WRITE(11,*)' OUTPUT'
0157      WRITE(11,*)'
0158      CALL BURCH(V,D,RH01,S,THETA,
0159      &           XN,E1,T1,T2,WT,WTCMC)
0160      WRITE(11,*)' BUMPER THICKNESS = ',T1,'CM'
0161      WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
0162      WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
0163      WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
0164      WRITE(11,*)'
0165      WRITE(11,*)'
0166      WRITE(11,*)'
0167      GO TO 10
0168      75      READ(10,*)V
0169      READ(10,*)D
0170      READ(10,*)RHOP
0171      READ(10,*)RH01
```

IMPACT5\$MAIN

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VAX FC

10-Aug-1987 11:29:03

SAI

```
0172      READ(10,*)RH02
0173      READ(10,*)SY1
0174      READ(10,*)SY2
0175      READ(10,*)THETA
0176      WRITE(11,*)'          PEN4'
0177      WRITE(11,*)'
0178      WRITE(11,*)'          INPUT'
0179      WRITE(11,*)'
0180      WRITE(11,*)'          PROJECTILE VELOCITY IN KM/SEC = ',V
0181      WRITE(11,*)'          PROJECTILE DIAMETER IN CM = ',D
0182      WRITE(11,*)'          PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0183      WRITE(11,*)'          BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0184      WRITE(11,*)'          WALL DENSITY IN GM/CUBIC CM = ',RH02
0185      WRITE(11,*)'          BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
0186      WRITE(11,*)'          WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
0187      WRITE(11,*)'          IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0188      WRITE(11,*)'
0189      CALL PEN4(V,D,RHOP,RH01,RH02,SY1,SY2,THETA,
0190      &           T1,T2,WT,WTCMC)
0191      WRITE(11,*)'          OUTPUT'
0192      WRITE(11,*)'
0193      WRITE(11,*)'          BUMPER THICKNESS = ',T1,'CM'
0194      WRITE(11,*)'          WALL THICKNESS = ',T2,'CM'
0195      WRITE(11,*)'          MIN. WEIGHT = ',WT,'CM'
0196      WRITE(11,*)'          CMC MIN. WEIGHT = ',WTCMC,'KG'
0197      WRITE(11,*)'
0198      GO TO 10
0199      10      CONTINUE
0200      STOP
0201      END
```

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VAX FOR
SAI_USR

```
0001      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0002      DMAX=0.24*H**V**-0.2
0003      IF(D.GT.DMAX)THEN
0004          WRITE(11,*)"NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH"
0005          GO TO 16
0006      ENDIF
0007      T1=1.93*V**0.18*D**1.91/H**0.91
0008      T2=1.86*T1
0009      WT=T1+T2
0010      WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
0011      WTCMC=12.*WTCMC
0012      16      CONTINUE
0013      RETURN
0014      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes					
0 \$CODE	214	PIC CON REL LCL	SHR	EXE	RD	NOWRT	LONG
1 \$PDATA	45	PIC CON REL LCL	SHR	NOEXE	RD	NOWRT	LONG
2 \$LOCAL	8	PIC CON REL LCL	NOSHR	NOEXE	RD	WRT	LONG
Total Space Allocated	267						

ENTRY POINTS

Address	Type	Name
0-00000000		NYSMITH

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	DMAX	AP-0000000C@	R*4	H
AP-00000014@	R*4	T2	AP-00000004@	R*4	V	AP-00000018@	R*4	WT

LABELS

Address	Label
0-000000D5	16

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VAX FO
SAI US

0001 SUBROUTINE BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
0002 & XN,E1,T1,T2,WT,WTCMC)
0003 ***** PEN4 *****
0004 T1=0.16
0005 V=V*3280.
0006 D=D/30.48
0007 RP=D/2.0
0008 RHOP=RHOP*1.94
0009 RHO1=RHO1*1.94
0010 RHO2=RHO2*1.94
0011 NITSP=0
0012 NITSP=NITSP+1
0013 NP1=0
0014 T1P=T1/30.48
0015 T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
0016 WT=T1P+T2P
0017 IF(NITSP.EQ.1)THEN
0018 T1P1=1.1*T1P
0019 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0020 WT1=T1P1+T2P1
0021 ENDIF
0022 IF(WT1.GT.WT)THEN
0023 T1P1=0.82*T1P1
0024 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0025 WT1=T1P1+T2P1
0026 590 IF(WT1.GT.WT)THEN
0027 GO TO 601
0028 ELSE
0029 T1P=T1P1
0030 T2P=T2P1
0031 WT=WT1
0032 NP1=NP1+1
0033 IF(NP1.EQ.100)THEN
0034 WRITE(11,*)"NO CONVERGENCE IN PEN4"
0035 GO TO 557
0036 ENDIF
0037 T1P1=0.9*T1P1
0038 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0039 WT1=T1P1+T2P1
0040 GO TO 590
0041 ENDIF
0042 ELSE
0043 579 T1P=T1P1
0044 T2P=T2P1
0045 WT=WT1
0046 T1P1=1.1*T1P1
0047 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0048 WT1=T1P1+T2P1
0049 IF(WT1.GT.WT)THEN
0050 GO TO 601
0051 ELSE
0052 NP1=NP1+1
0053 IF(NP1.EQ.100)THEN
0054 WRITE(11,*)"NO CONVERGENCE IN PEN4"
0055 GO TO 557
0056 ENDIF
0057 GO TO 579

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SAI_USR

```
0058      ENDIF
0059      ENDIF
0060  601  CONTINUE
0061      D=30.48*D
0062      RHOP=RHOP/1.94
0063      RH01=RH01/1.94
0064      RH02=RH02/1.94
0065      T1P=30.48*T1P
0066      T2P=30.48*T2P
0067      IF(T1P/D.LE.0.4)VF=4100
0068      IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0069      VF=VF+4000.
0070      IF(V.LE.VF)THEN
0071          WRITE(11,*)'INSIDE OF PEN4 LIMITS'
0072          T1=T1P
0073          T2=T2P
0074          GO TO 1102
0075      ENDIF
0076  557  CONTINUE
0077 ***** WILKINSON *****
0078      V=V/3280.
0079      T1=0.604*D**2.*RHOP/S
0080      T1=T1*SQRT(V/(XL2*RH01*RH02))
0081      RATIO=D*RHOP/(T1*RH01)
0082      IF(RATIO.GT.1.0)T2=T1
0083      IF(RATIO.LE.1.0)T2=T1/RATIO
0084 ***** MODIFIED BURCH *****
0085      VB=V*3280.
0086      DB=D/2.54
0087      CM=SQRT(E1/RH01)
0088      CM=CM/30.48
0089      SB=S/2.54
0090      IF(THETA.LE.0.001)GO TO 125
0091      CHI=TAN(THETA)-0.5
0092      F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0093      F2=F2+(1.7-12.*T1B/D)*CHI
0094      F3=0.32*(T1B/D)**0.83
0095      F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0096      T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0097      T2F=T2F*(D/S)**0.71
0098      T2N=F3*(CM/V)**1.33*D/XN
0099      IF(T2N.GE.T2F)T2B=T2N
0100      IF(T2N.LT.T2F)T2B=T2F
0101      T2B=T2B*2.54
0102      IF(T2B.GT.T2)NREGION=3
0103      IF(T2B.GT.T2)T2=T2B
0104      GO TO 155
0105  125  CONTINUE
0106      T1B1=T1/2.54
0107      NITSB=0
0108      XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0109      VDELT A=0.0
0110      DELTA3=0.52
0111  1099  DELTA2=2.33*(1.-1.57*DELTA3)
0112      DELTA1=1.33*(2.*DELTA3-1.)
0113      VDELT A1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0114      VDELT A1=VDELT A1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
```

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```
0115 IF(VDELT A1.LT.VDELT A)THEN
0116   DELTA1=1.33*(2.*DELTA3-1.04)
0117   T1B=DELTA1*VDELT A
0118   T2B=VDELT A-T1B
0119   GO TO 499
0120 ENDIF
0121 VDELT A=VDELT A1
0122 DELTA3=DELTA3+0.02
0123 IF(DELTA3.GT.0.63)THEN
0124   T1B=DELTA1*VDELT A
0125   T2B=VDELT A-T1B
0126   GO TO 499
0127 ENDIF
0128 GO TO 1099
0129 499 CONTINUE
0130 ***** COMPARISON OF MODIFIED BURCH AND WILKINSON *****
0131 199 CONTINUE
0132   T10W=T1/2.54
0133   F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
0134   T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
0135   T2BT10W=T2BT10W/SB**0.71
0136   T2BT10W=T2BT10W*2.54
0137   RATIOB=(DB*RHOP)/(RHO1*T1B)
0138   T2WT10B=0.364*D**3.*RHOP*V/(XL2*RHO2*S**2.)
0139   IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
0140   IF(T2BT10W.GT.T2)T2=T2BT10W
0141   T2B=T2B*2.54
0142   IF(T2WT10B.GT.T2B)T2B=T2WT10B
0143   T1B=T1B*2.54
0144   IF(T1B+T2B.LT.T1+T2)THEN
0145     T1=T1B
0146     T2=T2B
0147 ENDIF
0148 155 CONTINUE
0149 1102 IF(T2.LE.0.01)THEN
0150   WRITE(11,*)'PRESSURE CONSTRAINT ON WALL IN EFFECT'
0151   SIGMA=SY2/144.
0152   T2=3099.1/SIGMA
0153   ENDIF
0154   WT=T1+T2
0155   R12=211.
0156   R22=211.+T2
0157   R11=211.+T2+S
0158   R21=211.+T1+T2+S
0159   VB=4.27*(R21**2.-R11**2.)
0160   VW=4.27*(R22**2.-R12**2.)
0161   WTCMC=RHO1*VB+RHO2*VW
0162   RETURN
0163 156 END
```

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```
0001 FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
0002 F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
0003 F1=F1-4.18
0004 FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
0005 RETURN
0006 END
```

PROGRAM SECTIONS

Name	Bytes	Attributes						
0 \$CODE	163	PIC CON REL LCL	SHR	EXE	RD	NOWRT	LONG	
2 \$LOCAL	4	PIC CON REL LCL	NOSHR	NOEXE	RD	WRT	LONG	
Total Space Allocated	167							

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2B

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000010@	R*4	CM	AP-00000004@	R*4	DB	**	R*4	F1
AP-00000008@	R*4	T1B	AP-00000014@	R*4	VB	AP-0000000C@	R*4	XN

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VAX FOR
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```
0001      FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0002          A=1.33*RHOP*(V*RP)**2.
0003          B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
0004          C=1.33*RHOP*RP**2.0
0005          D1=RP*RH01/COS(THETA)
0006          XK1=1.67*(RHOP/(2.*SY2))**0.31
0007          XK1=XK1*(0.281*D*RHOP/RH02)**0.33
0008          XK1=XK1*COS(THETA)
0009          C1P1=(A-B*T1P)/(C+D1*T1P)
0010          IF(C1P1.LE.0.001)THEN
0011              FT2P=0.0
0012              GO TO 999
0013          ENDIF
0014          FT2P=XK1*C1P1**0.31
0015      999      RETURN
0016      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes	RD	NOWRT	LONG
0 \$CODE	222	PIC CON REL LCL SHR EXE			
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE	RD	WRT	LONG
Total Space Allocated	226				

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2P

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
**	R*4	A	**	R*4	B	**	R*4	C
AP-00000020@	R*4	D	**	R*4	D1	AP-00000018@	R*4	RH01
AP-00000004@	R*4	RHOP	AP-00000000C@	R*4	RP	AP-00000010@	R*4	SY1
AP-00000028@	R*4	T1P	AP-00000014@	R*4	THETA	AP-00000008@	R*4	V

LABELS

Address	Label
0-000000D9	999

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```
0001      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0002      V=V*1.E05
0003      T1=0.009*SQRT(V)*RHOP*D**2.0
0004      T1=T1/(S*RHO**1.5)
0005      T2=T1
0006      WT=T1+T2
0007      R12=211.
0008      R22=211.+T2
0009      R11=211.+T2+S
0010      R21=211.+T1+T2+S
0011      VB=4.27*(R21**2.-R11**2.)
0012      VW=4.27*(R22**2.-R12**2.)
0013      WTCMC=RHO*(VB+VW)
0014      RETURN
0015      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	159	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	159	

ENTRY POINTS

Address	Type	Name
0-00000000		MADDEN

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	R11	**	R*4	R12
**	R*4	R22	AP-00000014@	R*4	RHO	AP-0000000C@	R*4	RHOP
AP-00000018@	R*4	T1	AP-0000001C@	R*4	T2	AP-00000004@	R*4	V
**	R*4	VW	AP-00000020@	R*4	WT	AP-00000024@	R*4	WTCMC

FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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```
0001      SUBROUTINE WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,  
0002          &           T1,T2,WT,WTCMC)  
0003          T1=0.604*D**2.*RHOP/S  
0004          T1=T1*SQRT(V/(XL2*RHO1*RHO2))  
0005          RATIO=D*RHOP/(T1*RHO1)  
0006          IF(RATIO.GT.1.0)T2=T1  
0007          IF(RATIO.LE.1.0)T2=T1/RATIO  
0008          WT=T1+T2  
0009          R12=211.  
0010          R22=211.+T2  
0011          R11=211.+T2+S  
0012          R21=211.+T1+T2+S  
0013          VB=4.27*(R21**2.-R11**2.)  
0014          VW=4.27*(R22**2.-R12**2.)  
0015          WTCMC=RHO1*VB+RHO2*VW  
0016          RETURN  
0017          END
```

PROGRAM SECTIONS

Name	Bytes	Attributes									
0 \$CODE	181	PIC CON REL LCL	SHR	EXE	RD	NOWRT	LONG				
Total Space Allocated	181										

ENTRY POINTS

Address	Type	Name
0-00000000		WILKINSON

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	R11	**	R*4	R12
**	R*4	R22	**	R*4	RATIO	AP-000000010@	R*4	RHO1
AP-0000000C@	R*4	RHOP	AP-000000018@	R*4	S	AP-000000020@	R*4	T1
AP-00000004@	R*4	V	**	R*4	VB	**	R*4	VW
AP-0000002C@	R*4	WTCMC	AP-00000001C@	R*4	XL2			

FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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0001 ***** MODIFIED BURCH *****
0002 SUBROUTINE BURCH(V,D,RHO1,S,THETA,
0003 & XN,E1,T1,T2,WT,WTCMC)
0004 VB=V*3280.
0005 DB=D/2.54
0006 CM=SQRT(E1/RHO1)
0007 CM=CM/30.48
0008 SB=S/2.54
0009 IF(THETA.LE.0.001)GO TO 425
0010 CHI=TAN(THETA)-0.5
0011 F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0012 F2=F2+(1.7-12.*T1B/D)*CHI
0013 F3=0.32*(T1B/D)**0.83
0014 F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0015 T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0016 T2F=T2F*(D/S)**0.71
0017 T2N=F3*(CM/V)**1.33*D/XN
0018 IF(T2N.GE.T2F)T2B=T2N
0019 IF(T2N.LT.T2F)T2B=T2F
0020 T2B=T2B*2.54
0021 IF(T2B.GT.T2)NREGION=3
0022 IF(T2B.GT.T2)T2=T2B
0023 GO TO 499
0024 425 CONTINUE
0025 NITSB=0
0026 XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0027 VDELT A=0.0
0028 DELTA3=0.52
0029 1099 DELTA2=2.33*(1.-1.57*DELTA3)
0030 DELTA1=1.33*(2.*DELTA3-1.)
0031 VDELT A1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0032 VDELT A1=VDELT A1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
0033 IF(VDELT A1.LT.VDELT A)THEN
0034 DELTA1=1.33*(2.*DELTA3-1.04)
0035 T1=DELTA1*VDELT A
0036 T2=VDELT A-T1
0037 GO TO 499
0038 ENDIF
0039 VDELT A=VDELT A1
0040 DELTA3=DELTA3+0.02
0041 IF(DELTA3.GT.0.63)THEN
0042 T1=DELTA1*VDELT A
0043 T2=VDELT A-T1
0044 GO TO 499
0045 ENDIF
0046 GO TO 1099
0047 499 CONTINUE
0048 T1=T1*2.54
0049 T2=T2*2.54
0050 WT=T1+T2
0051 R12=211.
0052 R22=211.+T2
0053 R11=211.+T2+S
0054 R21=211.+T1+T2+S
0055 VB=4.27*(R21**2.-R11**2.)
0056 VW=4.27*(R22**2.-R12**2.)
0057 WTCMC=RHO1*VB+2.81*VW

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0001 SUBROUTINE PEN4(V,D,RHOP,RHO1,RHO2,SY1,SY2,THETA,
0002 & T1,T2,WT,WTCMC)
0003 T1=0.16
0004 V=V*3280.
0005 D=D/30.48
0006 RP=D/2.0
0007 RHOP=RHOP*1.94
0008 RHO1=RHO1*1.94
0009 RHO2=RHO2*1.94
0010 NITSP=0
0011 NITSP=NITSP+1
0012 NP1=0
0013 T1P=T1/30.48
0014 T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
0015 WT=T1P+T2P
0016 IF(NITSP.EQ.1)THEN
0017 T1P1=1.1*T1P
0018 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0019 WT1=T1P1+T2P1
0020 ENDIF
0021 IF(WT1.GT.WT)THEN
0022 T1P1=0.82*T1P1
0023 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0024 WT1=T1P1+T2P1
0025 588 IF(WT1.GT.WT)THEN
0026 GO TO 599
0027 ELSE
0028 T1P=T1P1
0029 T2P=T2P1
0030 WT=WT1
0031 NP1=NP1+1
0032 IF(NP1.EQ.100)THEN
0033 WRITE(11,*)"NO CONVERGENCE IN PEN4"
0034 GO TO 555
0035 ENDIF
0036 T1P1=0.9*T1P1
0037 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0038 WT1=T1P1+T2P1
0039 GO TO 588
0040 ENDIF
0041 ELSE
0042 577 T1P=T1P1
0043 T2P=T2P1
0044 WT=WT1
0045 T1P1=1.1*T1P1
0046 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0047 WT1=T1P1+T2P1
0048 IF(WT1.GT.WT)THEN
0049 GO TO 599
0050 ELSE
0051 NP1=NP1+1
0052 IF(NP1.EQ.100)THEN
0053 WRITE(11,*)"NO CONVERGENCE IN PEN4"
0054 GO TO 555
0055 ENDIF
0056 GO TO 577
0057 ENDIF

PEN4

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0058      ENDIF
0059  599  CONTINUE
0060      D=30.48*D
0061      T1P=30.48*T1P
0062      T2P=30.48*T2P
0063      IF(T1P/D.LE.0.4)VF=4100
0064      IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0065      VF=VF+4000.
0066      IF(V.GT.VF)THEN
0067          WRITE(11,*)'OUTSIDE OF PEN4 LIMITS'
0068          GO TO 1100
0069      ENDIF
0070      T1=T1P
0071      T2=T2P
0072  555  CONTINUE
0073      WT=T1+T2
0074      R12=211.
0075      R22=211.+T2
0076      R11=211.+T2+10.
0077      R21=211.+T1+T2+10.
0078      VB=4.27*(R21**2.-R11**2.)
0079      VW=4.27*(R22**2.-R12**2.)
0080      WTCMC=RHO1*VB+RH02*VW
0081  1100  RETURN
0082      END

```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	775	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	44	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	120	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	939	

ENTRY POINTS

Address	Type	Name
0-00000000		PEN4

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	I*4	NITSP	**	I*4	NP1
**	R*4	R12	**	R*4	R21	**	R*4	R22
AP-00000014@	R*4	RH02	AP-0000000C@	R*4	RHOP	2-00000000	R*4	RP
AP-0000001C@	R*4	SY2	AP-00000024@	R*4	T1	2-00000004	R*4	T1P
AP-00000028@	R*4	T2	**	R*4	T2P	**	R*4	T2P1
AP-00000004@	R*4	V	**	R*4	VB	2-0000000C	R*4	VF

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SAIC

IMPACT5V

IMPACT5V is a spacecraft protective systems design optimization code similar to IMPACT5. IMPACT5V differs from IMPACT5 in that the optimal design is weighted according to the chosen space debris velocity probability distribution. IMPACT5V employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, and Burch predictors. Inputs vary depending on the predictor used, however, typical inputs include the space debris velocity distribution file, projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5V is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. The velocity distribution files for 500 Km altitude and 30 degree inclination (500KM30DEG.DAT) and 60 degree inclination (500KM60 DEG.DAT) follow. The file being used must be assigned to FOR012 before running IMPACT5V. Sample input (IMPACT5V.IN), output (IMPACT5V.OUT), and program listing (IMPACT5V.LIS) follow the velocity distribution files.

SAC

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1	0.005
2	0.005
3	0.02
4	0.05
5	0.10
6	0.05
7	0.075
8	0.08
9	0.07
10	0.23
11	0.155
12	0.08
13	0.05
14	0.02
15	0.005
16	0.005

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1	0.01
2	0.01
3	0.01
4	0.01
5	0.03
6	0.03
7	0.01
8	0.01
9	0.005
10	0.09
11	0.09
12	0.07
13	0.28
14	0.28
15	0.065
16	0.005

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SAIC

5 !NUMBER OF CASES
1 !NYSMITH PREDICTOR
0.84 !PROJ. DIAMETER IN CM
10. !BUMPER/WALL SEPARATION IN CM
2 !BOEING PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
2.81 !WALL DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0.401 !WALL MATERIAL CONSTANT
7344000. !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000. !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0. !IMPACT ANGLE FROM NORMAL
0.85 !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11 !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3 !MADDEN PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
2.81 !BUMPER/WALL DENSITY IN GM/CUBIC CM
4 !WILKINSON PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
2.81 !WALL DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0.401 !WALL MATERIAL CONSTANT
5 !BURCH PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0. !IMPACT ANGLE FROM NORMAL
0.85 !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11 !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC

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OF POOR QUALITY.

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NYSMITH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2498978 CM
WALL THICKNESS = 0.4648098 CM
MIN. WEIGHT = 0.7147076 CM
CMC MIN. WEIGHT = 3685.385 KG

BOEING

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

INSIDE OF PEN4 LIMITS

INSIDE OF PEN4 LIMITS

OUTPUT

BUMPER THICKNESS = 0.1605087 CM
WALL THICKNESS = 0.5884032 CM
MIN. WEIGHT = 0.7489119 CM
CMC MIN. WEIGHT = 3837.381 KG

MADDEN

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.3522651 CM
WALL THICKNESS = 0.3522651 CM
MIN. WEIGHT = 0.7045302 CM
CMC MIN. WEIGHT = 3657.869 KG

WILKINSON

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.1978996 CM
WALL THICKNESS = 0.1978996 CM
MIN. WEIGHT = 0.3957993 CM
CMC MIN. WEIGHT = 2053.512 KG

MODIFIED BURCH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 0.1434212 CM
WALL THICKNESS = 0.6418241 CM
MIN. WEIGHT = 0.7852453 CM
CMC MIN. WEIGHT = 4017.877 KG

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VAX FORTRAN
SAI_USRDISK

```
0001      DIMENSION XPV(16)
0002      OPEN(UNIT=12,TYPE='OLD',ACCESS='SEQUENTIAL')
0003      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5V.IN',ACCESS='SEQUENTIAL')
0004      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5V.OUT',ACCESS='SEQUENTIAL')
0005      DO 24 I=1,16
0006          READ(12,*)IV,XPV(IV)
0007 24      CONTINUE
0008      READ(10,*)NRUNS
0009      DO 10 I=1,NRUNS
0010          READ(10,*)NCODE
0011          IF(NCODE.EQ.1)GO TO 25
0012          IF(NCODE.EQ.2)GO TO 35
0013          IF(NCODE.EQ.3)GO TO 45
0014          IF(NCODE.EQ.4)GO TO 55
0015          IF(NCODE.EQ.5)GO TO 65
0016 25      READ(10,*)D
0017      READ(10,*)H
0018      WRITE(11,*)'      NYSMITH'
0019      WRITE(11,*)'
0020      WRITE(11,*)'      INPUT'
0021      WRITE(11,*)'
0022      WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
0023      WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',H
0024      WRITE(11,*)'
0025      T1T=0.0
0026      T2T=0.0
0027      DO 26 J=1,16
0028          V=FLOAT(J)
0029          CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0030          T1T=T1T+T1*Xpv(J)
0031          T2T=T2T+T2*Xpv(J)
0032 26      CONTINUE
0033          T1=T1T
0034          T2=T2T
0035          WT=T1+T2
0036          WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
0037          WTCMC=12.*WTCMC
0038          WRITE(11,*)'      OUTPUT'
0039          WRITE(11,*)'
0040          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0041          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0042          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0043          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0044          WRITE(11,*)'
0045          WRITE(11,*)'
0046          WRITE(11,*)'
0047          GO TO 10
0048 35      READ(10,*)D
0049          READ(10,*)RHOP
0050          READ(10,*)RH01
0051          READ(10,*)RH02
0052          READ(10,*)S
0053          READ(10,*)XL2
0054          READ(10,*)SY1
0055          READ(10,*)SY2
0056          READ(10,*)THETA
0057          READ(10,*)XN
```

```

58      READ(10,*)E1
59      WRITE(11,*)'          BOEING'
60      WRITE(11,*)'
61      WRITE(11,*)'          INPUT'
62      WRITE(11,*)'
63      WRITE(11,*)'          PROJECTILE DIAMETER IN CM = ',D
64      WRITE(11,*)'          PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
65      WRITE(11,*)'          BUMPER DENSITY IN GM/CUBIC CM = ',RH01
66      WRITE(11,*)'          WALL DENSITY IN GM/CUBIC CM = ',RH02
67      WRITE(11,*)'          BUMPER/WALL SEPARATION IN CM = ',S
68      WRITE(11,*)'          WALL MATERIAL CONSTANT = ',XL2
69      WRITE(11,*)'          BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
70      WRITE(11,*)'          WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
71      WRITE(11,*)'          IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
72      WRITE(11,*)'          NUMBER OF PLATES TO PENETRATE AFTER FIRST',
73      &           '          BUMPER = ',XN
74      &           '          BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
75      &           '          SEC = ',E1
76      WRITE(11,*)'
77      T1T=0.0
78      T2T=0.0
79      DO 36 J=1,16
80      V=FLOAT(J)
81      CALL BOEING(V,D,RHOP,RH01,RH02,S,XL2,SY1,SY2,THETA,
82           XN,E1,T1,T2,WT,WTCMC)
83      &           T1T=T1T+XPV(J)*T1
84      &           T2T=T2T+XPV(J)*T2
85      36    CONTINUE
86      T1=T1T
87      T2=T2T
88      WT=T1+T2
89      R12=211.
90      R22=211.+T2
91      R11=211.+T2+S
92      R21=211.+T1+T2+S
93      VB=4.27*(R21**2.-R11**2.)
94      VW=4.27*(R22**2.-R12**2.)
95      WTCMC=RH01*VB+RH02*VW
96      WRITE(11,*)'          OUTPUT'
97      WRITE(11,*)'
98      WRITE(11,*)'          BUMPER THICKNESS = ',T1,'CM'
99      WRITE(11,*)'          WALL THICKNESS = ',T2,'CM'
100     WRITE(11,*)'          MIN. WEIGHT = ',WT,'CM'
101     WRITE(11,*)'          CMC MIN. WEIGHT = ',WTCMC,'KG'
102     WRITE(11,*)'
103     WRITE(11,*)'
104     WRITE(11,*)'
105     GO TO 10
106    45    READ(10,*)D
107    READ(10,*)RHOP
108    READ(10,*)S
109    READ(10,*)RHO
110    WRITE(11,*)'          MADDEN'
111    WRITE(11,*)'
112    WRITE(11,*)'          INPUT'
113    WRITE(11,*)'
114    WRITE(11,*)'          PROJECTILE DIAMETER IN CM = ',D

```

```
0115      WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0116      WRITE(11,*)' BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
0117      WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
0118      WRITE(11,*)'
0119      T1T=0.0
0120      T2T=0.0
0121      DO 46 J=1,16
0122      V=FLOAT(J)
0123      CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0124      T1T=T1T+T1*Xpv(J)
0125      T2T=T2T+T2*Xpv(J)
0126      46   CONTINUE
0127      T1=T1T
0128      T2=T2T
0129      WT=T1+T2
0130      R12=211.
0131      R22=211.+T2
0132      R11=211.+T2+S
0133      R21=211.+T1+T2+S
0134      VB=4.27*(R21**2.-R11**2.)
0135      VW=4.27*(R22**2.-R12**2.)
0136      WTCMC=RHO*(VB+VW)
0137      WRITE(11,*)' OUTPUT'
0138      WRITE(11,*)'
0139      WRITE(11,*)' BUMPER THICKNESS = ',T1,'CM'
0140      WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
0141      WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
0142      WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
0143      WRITE(11,*)'
0144      WRITE(11,*)'
0145      WRITE(11,*)'
0146      GO TO 10
0147      55   READ(10,*)D
0148      READ(10,*)RHOP
0149      READ(10,*)RH01
0150      READ(10,*)RH02
0151      READ(10,*)S
0152      READ(10,*)XL2
0153      WRITE(11,*)' WILKINSON'
0154      WRITE(11,*)'
0155      WRITE(11,*)' INPUT'
0156      WRITE(11,*)'
0157      WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
0158      WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
0159      WRITE(11,*)' BUMPER DENSITY IN GM/CUBIC CM = ',RH01
0160      WRITE(11,*)' WALL DENSITY IN GM/CUBIC CM = ',RH02
0161      WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
0162      WRITE(11,*)' WALL MATERIAL CONSTANT = ',XL2
0163      WRITE(11,*)'
0164      T1T=0.0
0165      T2T=0.0
0166      DO 56 J=1,16
0167      V=FLOAT(J)
0168      CALL WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,
0169      &           T1,T2,WT,WTCMC)
0170      T1T=T1T+T1*Xpv(J)
0171      T2T=T2T+T2*Xpv(J)
```

```

0172      56    CONTINUE
0173          T1=T1T
0174          T2=T2T
0175          WT=T1+T2
0176          R12=211.
0177          R22=211.+T2
0178          R11=211.+T2+S
0179          R21=211.+T1+T2+S
0180          VB=4.27*(R21**2.-R11**2.)
0181          VW=4.27*(R22**2.-R12**2.)
0182          WTCMC=RHO1*VB+RHO2*VW
0183          WRITE(11,*)'           OUTPUT'
0184          WRITE(11,*)'
0185          WRITE(11,*)'           BUMPER THICKNESS = ',T1,'CM'
0186          WRITE(11,*)'           WALL THICKNESS = ',T2,'CM'
0187          WRITE(11,*)'           MIN. WEIGHT = ',WT,'CM'
0188          WRITE(11,*)'           CMC MIN. WEIGHT = ',WTCMC,'KG'
0189          WRITE(11,*)'
0190          WRITE(11,*)'
0191          WRITE(11,*)'
0192          GO TO 10
0193      65    READ(10,*)D
0194          READ(10,*)RHO1
0195          READ(10,*)S
0196          READ(10,*)THETA
0197          READ(10,*)XN
0198          READ(10,*)E1
0199      ***** MODIFIED BURCH *****
0200          WRITE(11,*)'           MODIFIED BURCH'
0201          WRITE(11,*)'
0202          WRITE(11,*)'           INPUT'
0203          WRITE(11,*)'
0204          WRITE(11,*)'           PROJECTILE DIAMETER IN CM = ',D
0205          WRITE(11,*)'           BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
0206          WRITE(11,*)'           BUMPER/WALL SEPARATION IN CM = ',S
0207          WRITE(11,*)'           IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
0208          WRITE(11,*)'           NUMBER OF PLATES TO PENETRATE AFTER FIRST',
0209          &          WRITE(11,*)'           BUMPER = ',XN
0210          &          WRITE(11,*)'           BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
0211          &          WRITE(11,*)'           SEC = ',E1
0212          WRITE(11,*)'
0213          T1T=0.0
0214          T2T=0.0
0215          DO 66 J=1,16
0216          V=FLOAT(J)
0217          CALL BURCH(V,D,RHO1,S,THETA,
0218          &          XN,E1,T1,T2,WT,WTCMC)
0219          T1T=T1T+T1*XPV(J)
0220          T2T=T2T+T2*XPV(J)
0221      66    CONTINUE
0222          T1=T1T
0223          T2=T2T
0224          WT=T1+T2
0225          R12=211.
0226          R22=211.+T2
0227          R11=211.+T2+S
0228          R21=211.+T1+T2+S

```

IMPACT5V\$MAIN

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```

0229      VB=4.27*(R21**2.-R11**2.)
0230      VW=4.27*(R22**2.-R12**2.)
0231      WTCMC=RHO1*VB+2.81*VW
0232      WRITE(11,*)'      OUTPUT'
0233      WRITE(11,*)'
0234      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
0235      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
0236      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
0237      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
0238      WRITE(11,*)'
0239      WRITE(11,*)'
0240      WRITE(11,*)'
0241      GO TO 10
0242      10      CONTINUE
0243      STOP
0244      END

```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	4728	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	741	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	692	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	6161	

ENTRY POINTS

Address	Type	Name
0-00000000		IMPACT5V\$MAIN

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
2-00000004C	R*4	D	2-00000008C	R*4	E1	2-000000050	R*4	H
2-00000040	I*4	IV	**	I*4	J	2-000000048	I*4	NCODE
**	R*4	R11	**	R*4	R12	**	R*4	R21
2-00000090	R*4	RHO	2-00000006C	R*4	RHO1	2-000000070	R*4	RH02
2-00000074	R*4	S	2-00000007C	R*4	SY1	2-000000080	R*4	SY2
**	R*4	T1T	2-00000005C	R*4	T2	**	R*4	T2T
2-00000054	R*4	V	**	R*4	VB	**	R*4	VW
2-00000064	R*4	WTCMC	2-000000078	R*4	XL2	2-000000088	R*4	XN

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```
0001      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
0002      DMAX=0.24*H**V**-0.2
0003      IF(D.GT.DMAX)THEN
0004          WRITE(11,*)'    NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
0005          GO TO 16
0006      ENDIF
0007      T1=1.93*V**0.18*D**1.91/H**0.91
0008      T2=1.86*T1
0009      16      CONTINUE
0010      RETURN
0011      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	150	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	49	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	8	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	207	

ENTRY POINTS

Address	Type	Name
0-00000000		NYSMITH

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	DMAX	AP-0000000C@	R*4	H
AP-00000014@	R*4	T2	AP-00000004@	R*4	V	AP-00000018@	R*4	WT

LABELS

Address	Label
0-00000095	16

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VAX FORTRAN
CAT USRDIS

```

0001      SUBROUTINE BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
0002          &           XN,E1,T1,T2,WT,WTCMC)
0003  ***** PEN4 *****
0004      T1=0.16
0005      V=V*3280.
0006      D=D/30.48
0007      RP=D/2.0
0008      RHOP=RHOP*1.94
0009      RHO1=RHO1*1.94
0010      RHO2=RHO2*1.94
0011      NITSP=0
0012      NITSP=NITSP+1
0013      NP1=0
0014      T1P=T1/30.48
0015      T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
0016      WT=T1P+T2P
0017      IF(NITSP.EQ.1)THEN
0018          T1P1=1.1*T1P
0019          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0020          WT1=T1P1+T2P1
0021      ENDIF
0022      IF(WT1.GT.WT)THEN
0023          T1P1=0.82*T1P1
0024          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0025          WT1=T1P1+T2P1
0026      590      IF(WT1.GT.WT)THEN
0027          GO TO 601
0028      ELSE
0029          T1P=T1P1
0030          T2P=T2P1
0031          WT=WT1
0032          NP1=NP1+1
0033          IF(NP1.EQ.100)THEN
0034              WRITE(11,*)' NO CONVERGENCE IN PEN4'
0035              GO TO 557
0036          ENDIF
0037          T1P1=0.9*T1P1
0038          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0039          WT1=T1P1+T2P1
0040          GO TO 590
0041      ENDIF
0042      ELSE
0043      579      T1P=T1P1
0044          T2P=T2P1
0045          WT=WT1
0046          T1P1=1.1*T1P1
0047          T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
0048          WT1=T1P1+T2P1
0049          IF(WT1.GT.WT)THEN
0050              GO TO 601
0051          ELSE
0052              NP1=NP1+1
0053              IF(NP1.EQ.100)THEN
0054                  WRITE(11,*)' NO CONVERGENCE IN PEN4'
0055                  GO TO 557
0056              ENDIF
0057              GO TO 579

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0058      ENDIF
0059      ENDIF
0060  601  CONTINUE
0061      D=30.48*D
0062      RHOP=RHOP/1.94
0063      RH01=RH01/1.94
0064      RH02=RH02/1.94
0065      T1P=30.48*T1P
0066      T2P=30.48*T2P
0067      IF(T1P/D.LE.0.4)VF=4100
0068      IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
0069      VF=VF+4000.
0070      IF(V.LE.VF)THEN
0071          WRITE(11,*)'    INSIDE OF PEN4 LIMITS'
0072          T1=T1P
0073          T2=T2P
0074          GO TO 1102
0075      ENDIF
0076  557  CONTINUE
0077 ***** WILKINSON *****
0078      V=V/3280.
0079      T1=0.604*D**2.*RHOP/S
0080      T1=T1*SQRT(V/(XL2*RH01*RH02))
0081      RATIO=D*RHOP/(T1*RH01)
0082      IF(RATIO.GT.1.0)T2=T1
0083      IF(RATIO.LE.1.0)T2=T1/RATIO
0084 ***** MODIFIED BURCH *****
0085      VB=V*3280.
0086      DB=D/2.54
0087      CM=SQRT(E1/RH01)
0088      CM=CM/30.48
0089      SB=S/2.54
0090      IF(THETA.LE.0.001)GO TO 125
0091      CHI=TAN(THETA)-0.5
0092      F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0093      F2=F2+(1.7-12.*T1B/D)*CHI
0094      F3=0.32*(T1B/D)**0.83
0095      F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0096      T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0097      T2F=T2F*(D/S)**0.71
0098      T2N=F3*(CM/V)**1.33*D/XN
0099      IF(T2N.GE.T2F)T2B=T2N
0100      IF(T2N.LT.T2F)T2B=T2F
0101      T2B=T2B*2.54
0102      IF(T2B.GT.T2)NREGION=3
0103      IF(T2B.GT.T2)T2=T2B
0104      GO TO 155
0105  125  CONTINUE
0106      T1B1=T1/2.54
0107      NITSB=0
0108      XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0109      VDELT A=0.0
0110      DELTA3=0.52
0111  1099  DELTA2=2.33*(1.-1.57*DELTA3)
0112      DELTA1=1.33*(2.*DELTA3-1.)
0113      VDELT A1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0114      VDELT A1=VDELT A1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3

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0115 IF(VDELT A1.LT.VDELT A)THEN
0116   DELTA1=1.33*(2.*DELTA3-1.04)
0117   T1B=DELTA1*VDELT A
0118   T2B=VDELT A-T1B
0119   GO TO 499
0120 ENDIF
0121 VDELT A=VDELT A1
0122 DELTA3=DELTA3+0.02
0123 IF(DELTA3.GT.0.63)THEN
0124   T1B=DELTA1*VDELT A
0125   T2B=VDELT A-T1B
0126   GO TO 499
0127 ENDIF
0128 GO TO 1099
0129 499 CONTINUE
0130 ***** COMPARISON OF MODIFIED BURCH AND WILKINSON *****
0131 199 CONTINUE
0132   T10W=T1/2.54
0133   F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
0134   T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
0135   T2BT10W=T2BT10W/SB**0.71
0136   T2BT10W=T2BT10W*2.54
0137   RATIOB=(DB*RHOP)/(RH01*T1B)
0138   T2WT10B=0.364*D**3.*RHOP*V/(XL2*RH02*S**2.)
0139   IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
0140   IF(T2BT10W.GT.T2)T2=T2BT10W
0141   T2B=T2B*2.54
0142   IF(T2WT10B.GT.T2B)T2B=T2WT10B
0143   T1B=T1B*2.54
0144   IF(T1B+T2B.LT.T1+T2)THEN
0145     T1=T1B
0146     T2=T2B
0147   ENDIF
0148   155 CONTINUE
0149   1102 IF(T2.LE.0.01)THEN
0150     SIGMA=SY2/144.
0151     T2=3099.1/SIGMA
0152   ENDIF
0153   156 RETURN
0154   END

```

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```

0001 FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
0002 F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
0003 F1=F1-4.18
0004 FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
0005 RETURN
0006 END

```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	163	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	167	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2B

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000010@	R*4	CM	AP-00000004@	R*4	DB	**	R*4	F1
AP-00000008@	R*4	T1B	AP-00000014@	R*4	VB	AP-0000000C@	R*4	XN

```

0001 FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
0002 A=1.33*RHOP*(V*RP)**2.
0003 B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
0004 C=1.33*RHOP*RP**2.0
0005 D1=RP*RH01/COS(THETA)
0006 XK1=1.67*(RHOP/(2.*SY2))**0.31
0007 XK1=XK1*(0.281*D*RHOP/RH02)**0.33
0008 XK1=XK1*COS(THETA)
0009 C1P1=(A-B*T1P)/(C+D1*T1P)
0010 IF(C1P1.LE.0.001)THEN
0011   FT2P=0.0
0012   GO TO 999
0013 ENDIF
0014 FT2P=XK1*C1P1**0.31
0015 999 RETURN
0016 END

```

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PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	222	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	226	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2P

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
**	R*4	A	**	R*4	B	**	R*4	C
AP-00000020@	R*4	D	**	R*4	D1	AP-00000018@	R*4	RH01
AP-00000004@	R*4	RHOP	AP-0000000C@	R*4	RP	AP-00000010@	R*4	SY1
AP-00000028@	R*4	T1P	AP-00000014@	R*4	THETA	AP-00000008@	R*4	V

LABELS

Address	Label
0-000000D9	999

```

0001 SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
0002 V=V*1.E05
0003 T1=0.009*SQRT(V)*RHOP*D**2.0
0004 T1=T1/(S*RHO**1.5)
0005 T2=T1
0006 RETURN
0007 END

```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	69	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	69	

ENTRY POINTS

Address	Type	Name
0-00000000		MADDEN

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	AP-00000014@	R*4	RHO	AP-0000000C@	R*4	RHOP
AP-00000018@	R*4	T1	AP-0000001C@	R*4	T2	AP-00000004@	R*4	V
AP-00000024@	R*4	WTCMC						

FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

```

0001      SUBROUTINE WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
0002          &           T1,T2,WT,WTCMC)
0003          T1=0.604*D**2.*RHOP/S
0004          T1=T1*SQRT(V/(XL2*RHO1*RHO2))
0005          RATIO=D*RHOP/(T1*RHO1)
0006          IF(RATIO.GT.1.0)T2=T1
0007          IF(RATIO.LE.1.0)T2=T1/RATIO
0008          RETURN
0009          END

```

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PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	87	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	87	

ENTRY POINTS

Address	Type	Name
0-00000000		WILKINSON

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	RATIO	AP-00000010@	R*4	RHO1
AP-0000000C@	R*4	RHOP	AP-00000018@	R*4	S	AP-00000020@	R*4	T1
AP-00000004@	R*4	V	AP-00000028@	R*4	WT	AP-0000002C@	R*4	WTCMC

FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

```

0001 ***** MODIFIED BURCH *****
0002      SUBROUTINE BURCH(V,D,RHO1,S,THETA,
0003      &           XN,E1,T1,T2,WT,WTCMC)
0004      VB=V*3280.
0005      DB=D/2.54
0006      CM=SQRT(E1/RHO1)
0007      CM=CM/30.48
0008      SB=S/2.54
0009      IF(THETA.LE.0.001)GO TO 425
0010      CHI=TAN(THETA)-0.5
0011      F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
0012      F2=F2+(1.7-12.*T1B/D)*CHI
0013      F3=0.32*(T1B/D)**0.83
0014      F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
0015      T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
0016      T2F=T2F*(D/S)**0.71
0017      T2N=F3*(CM/V)**1.33*D/XN
0018      IF(T2N.GE.T2F)T2B=T2N
0019      IF(T2N.LT.T2F)T2B=T2F
0020      T2B=T2B*2.54
0021      IF(T2B.GT.T2)NREGION=3
0022      IF(T2B.GT.T2)T2=T2B
0023      GO TO 499
0024      425    CONTINUE
0025      NITSB=0
0026      XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
0027      VDELT A=0.0
0028      DELTA3=0.52
0029      1099   DELTA2=2.33*(1.-1.57*DELTA3)
0030      DELTA1=1.33*(2.*DELTA3-1.)
0031      VDELT A1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
0032      VDELT A1=VDELT A1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
0033      IF(VDELT A1.LT.VDELT A)THEN
0034          DELTA1=1.33*(2.*DELTA3-1.04)
0035          T1=DELTA1*VDELT A
0036          T2=VDELT A-T1
0037          GO TO 499
0038      ENDIF
0039      VDELT A=VDELT A1
0040      DELTA3=DELTA3+0.02
0041      IF(DELTA3.GT.0.63)THEN
0042          T1=DELTA1*VDELT A
0043          T2=VDELT A-T1
0044          GO TO 499
0045      ENDIF
0046      GO TO 1099
0047      499    CONTINUE
0048      T1=T1*2.54
0049      T2=T2*2.54
0050      RETURN
0051      END

```

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IMPACT5VM

IMPACT5VM is a spacecraft protective systems design optimization code similar to IMPACT5V. IMPACT5VM differs from IMPACT5V in that the optimal design is weighted according to the chosen meteoroid velocity probability distribution. IMPACT5VM employs the Geometric Programming optimization technique in evaluating a number of nonlinear piecewise continuous, functional impact predictors. These include the Nysmith, Boeing, Madden, Wilkinson, and Burch predictors. Inputs vary depending on the predictor used, however, typical inputs include the meteoroid velocity distribution file, projectile characteristics (as determined from METEOR1 or DEBRIS1), design material properties, and general design configuration. In particular, IMPACT5VM is an optimization code for a single bumper, single wall configuration. Outputs include the optimal design thicknesses (bumper and wall) and the minimum design weight. The velocity distribution file for meteoroids, (METVEL.IN), follows. The file being used must be assigned to FOR012 before running IMPACT5VM. Sample input (IMPACT5VM.IN), output (IMPACT5VM.OUT), and program listing (IMPACT5VM.LIS) follow the velocity distribution file.

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SAIC

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10	.045
11	.045
12	.045
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16	.26
17	.26
18	.26
19	.14
20	.14
21	.14
22	.10
23	.10
24	.10
25	.06
26	.06
27	.06
28	.05
29	.05
30	.05
31	.025
32	.025
33	.025
34	.015
35	.015
36	.015
37	.012
38	.012
39	.012
40	.011
41	.011
42	.011
43	.009
44	.009
45	.009
46	.0075
47	.0075
48	.0075
49	.0075
50	.0075
51	.0075
52	.0075
53	.0075
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SAC

69 .0075
70 .0075
71 .0075
72 .0075

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SWC

5 !NUMBER OF CASES
1 !NYSMITH PREDICTOR
0.84 !PROJ. DIAMETER IN CM
10. !BUMPER/WALL SEPARATION IN CM
2 !BOEING PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
2.81 !WALL DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0.401 !WALL MATERIAL CONSTANT
7344000. !BUMPER YIELD STRENGTH IN LB/SQUARE FOOT
7344000. !WALL YIELD STRENGTH IN LB/SQUARE FOOT
0. !IMPACT ANGLE FROM NORMAL
0.85 !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11 !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC
3 !MADDEN PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
2.81 !BUMPER/WALL DENSITY IN GM/CUBIC CM
4 !WILKINSON PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !PROJ. DENSITY IN GM/CUBIC CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
2.81 !WALL DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0.401 !WALL MATERIAL CONSTANT
5 !BURCH PREDICTOR
0.84 !PROJ. DIA. IN CM
2.81 !BUMPER DENSITY IN GM/CUBIC CM
10. !BUMPER/WALL SEPARATION IN CM
0. !IMPACT ANGLE FROM NORMAL
0.85 !NUMBER OF PLATES TO PENETRATE AFTER 1ST BUMPER
7.239E11 !YOUNG'S MODULUS FOR BUMPER IN GM/CM-SQUARE SEC

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SALE

NYSMITH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.2964782 CM
WALL THICKNESS = 0.5514496 CM
MIN. WEIGHT = 0.8479279 CM
CMC MIN. WEIGHT = 4373.689 KG

BOEING

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000
BUMPER YIELD STRENGTH IN LB/SQUARE FT = 7344000.
WALL YIELD STRENGTH IN LB/SQUARE FT = 7344000.
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 0.3065161 CM
WALL THICKNESS = 0.3286171 CM
MIN. WEIGHT = 0.6351332 CM
CMC MIN. WEIGHT = 3294.346 KG

MADDEN

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000

OUTPUT

BUMPER THICKNESS = 0.5543199 CM
WALL THICKNESS = 0.5543199 CM
MIN. WEIGHT = 1.108640 CM
CMC MIN. WEIGHT = 5761.344 KG

WILKINSON

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
PROJECTILE DENSITY IN GM/CUBIC CM = 2.810000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
WALL DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
WALL MATERIAL CONSTANT = 0.4010000

OUTPUT

BUMPER THICKNESS = 0.3114124 CM
WALL THICKNESS = 0.3114124 CM
MIN. WEIGHT = 0.6228247 CM
CMC MIN. WEIGHT = 3233.087 KG

MODIFIED BURCH

INPUT

PROJECTILE DIAMETER IN CM = 0.8400000
BUMPER DENSITY IN GM/CUBIC CM = 2.810000
BUMPER/WALL SEPARATION IN CM = 10.00000
IMPACT ANGLE FROM NORMAL IN DEGREES = 0.0000000E+00
NUMBER OF PLATES TO PENETRATE AFTER FIRST BUMPER = 0.8500000
BUMPER YOUNGS MODULUS IN GM/CM-SQUARE SEC = 7.2389997E+11

OUTPUT

BUMPER THICKNESS = 4.5066189E-02CM
WALL THICKNESS = 9.7935580E-02CM
MIN. WEIGHT = 0.1430018 CM
CMC MIN. WEIGHT = 735.0610 KG

17-Aug-1987 15:27:34
17-Aug-1987 15:19:56

VAX FORTRAN
SAI_USRDISK

```
)001      DIMENSION XPV(100)
)002      OPEN(UNIT=12,TYPE='OLD',ACCESS='SEQUENTIAL')
)003      OPEN(UNIT=10,TYPE='OLD',NAME='IMPACT5VM.IN',ACCESS='SEQUENTIAL')
)004      OPEN(UNIT=11,TYPE='NEW',NAME='IMPACT5VM.OUT',ACCESS='SEQUENTIAL')
)005      DO 24 I=1,64
)006          READ(12,*)IV,XPV(IV)
)007      24    CONTINUE
)008      READ(10,*)NRUNS
)009      DO 10 I=1,NRUNS
)010          READ(10,*)NCODE
)011          IF(NCODE.EQ.1)GO TO 25
)012          IF(NCODE.EQ.2)GO TO 35
)013          IF(NCODE.EQ.3)GO TO 45
)014          IF(NCODE.EQ.4)GO TO 55
)015          IF(NCODE.EQ.5)GO TO 65
)016      25    READ(10,*)D
)017          READ(10,*)H
)018          WRITE(11,*)'      NYSMITH'
)019          WRITE(11,*)'
)020          WRITE(11,*)'      INPUT'
)021          WRITE(11,*)'
)022          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
)023          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',H
)024          WRITE(11,*)'
)025          T1T=0.0
)026          T2T=0.0
)027          DO 26 J=1,64
)028              K=J+8
)029              V=FLOAT(K)
)030              CALL NYSMITH(V,D,H,T1,T2,WT,WTCMC)
)031              T1T=T1T+T1*XPV(K)
)032              T2T=T2T+T2*XPV(K)
)033      26    CONTINUE
)034          T1=T1T/3.1335
)035          T2=T2T/3.1335
)036          WT=T1+T2
)037          WTCMC=T1**2.+2.*T1*(211.+T2+H)+T2**2.+422.*T2
)038          WTCMC=12.*WTCMC
)039          WRITE(11,*)'      OUTPUT'
)040          WRITE(11,*)'
)041          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
)042          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
)043          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
)044          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
)045          WRITE(11,*)'
)046          WRITE(11,*)'
)047          WRITE(11,*)'
)048          GO TO 10
)049      35    READ(10,*)D
)050          READ(10,*)RHOP
)051          READ(10,*)RH01
)052          READ(10,*)RH02
)053          READ(10,*)S
)054          READ(10,*)XL2
)055          READ(10,*)SY1
)056          READ(10,*)SY2
)057          READ(10,*)THETA
```

```

)058      READ(10,*)XN
)059      READ(10,*)E1
)060      WRITE(11,*)'          BOEING'
)061      WRITE(11,*)'
)062      WRITE(11,*)'          INPUT'
)063      WRITE(11,*)'
)064      WRITE(11,*)'          PROJECTILE DIAMETER IN CM = ',D
)065      WRITE(11,*)'          PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
)066      WRITE(11,*)'          BUMPER DENSITY IN GM/CUBIC CM = ',RH01
)067      WRITE(11,*)'          WALL DENSITY IN GM/CUBIC CM = ',RH02
)068      WRITE(11,*)'          BUMPER/WALL SEPARATION IN CM = ',S
)069      WRITE(11,*)'          WALL MATERIAL CONSTANT = ',XL2
)070      WRITE(11,*)'          BUMPER YIELD STRENGTH IN LB/SQUARE FT = ',SY1
)071      WRITE(11,*)'          WALL YIELD STRENGTH IN LB/SQUARE FT = ',SY2
)072      WRITE(11,*)'          IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
)073      WRITE(11,*)'          NUMBER OF PLATES TO PENETRATE AFTER FIRST',
)074      &           '          BUMPER = ',XN
)075      &           WRITE(11,*)'          BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
)076      &           '          SEC = ',E1
)077
)078      WRITE(11,*)'          T1T=0.0
)079      T2T=0.0
)080      DO 36 J=1,64
)081      K=J+8
)082      V=FLOAT(K)
)083      CALL BOEING(V,D,RHOP,RH01,RH02,S,XL2,SY1,SY2,THETA,
)084      &           XN,E1,T1,T2,WT,WTCMC)
)085      T1T=T1T+XPV(K)*T1
)086      T2T=T2T+XPV(K)*T2
)087      36    CONTINUE
)088      T1=T1T/3.1335
)089      T2=T2T/3.1335
)090      WT=T1+T2
)091      R12=211.
)092      R22=211.+T2
)093      R11=211.+T2+S
)094      R21=211.+T1+T2+S
)095      VB=4.27*(R21**2.-R11**2.)
)096      VW=4.27*(R22**2.-R12**2.)
)097      WTCMC=RH01*VB+RH02*VW
)098      WRITE(11,*)'          OUTPUT'
)099
)100      WRITE(11,*)'          BUMPER THICKNESS = ',T1,'CM'
)101      WRITE(11,*)'          WALL THICKNESS = ',T2,'CM'
)102      WRITE(11,*)'          MIN. WEIGHT = ',WT,'CM'
)103      WRITE(11,*)'          CMC MIN. WEIGHT = ',WTCMC,'KG'
)104      WRITE(11,*)'
)105      WRITE(11,*)'
)106      WRITE(11,*)'
)107      GO TO 10
)108      45    READ(10,*)D
)109      READ(10,*)RHOP
)110      READ(10,*)S
)111      READ(10,*)RHO
)112      WRITE(11,*)'          MADDEN'
)113      WRITE(11,*)'
)114      WRITE(11,*)'          INPUT'

```

```

)115      WRITE(11,*)'
)116      WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
)117      WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
)118      WRITE(11,*)' BUMPER/WALL DENSITY IN GM/CUBIC CM = ',RHO
)119      WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
)120      WRITE(11,*)'
)121      T1T=0.0
)122      T2T=0.0
)123      DO 46 J=1,64
)124      K=J+8
)125      V=FLOAT(K)
)126      CALL MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
)127      T1T=T1T+T1*XPV(K)
)128      T2T=T2T+T2*XPV(K)
)129      CONTINUE
)130      T1=T1T/3.1335
)131      T2=T2T/3.1335
)132      WT=T1+T2
)133      R12=211.
)134      R22=211.+T2
)135      R11=211.+T2+S
)136      R21=211.+T1+T2+S
)137      VB=4.27*(R21**2.-R11**2.)
)138      VW=4.27*(R22**2.-R12**2.)
)139      WTCMC=RHO*(VB+VW)
)140      WRITE(11,*)' OUTPUT'
)141      WRITE(11,*)'
)142      WRITE(11,*)' BUMPER THICKNESS = ',T1,'CM'
)143      WRITE(11,*)' WALL THICKNESS = ',T2,'CM'
)144      WRITE(11,*)' MIN. WEIGHT = ',WT,'CM'
)145      WRITE(11,*)' CMC MIN. WEIGHT = ',WTCMC,'KG'
)146      WRITE(11,*)'
)147      WRITE(11,*)'
)148      WRITE(11,*)'
)149      GO TO 10
)150      55      READ(10,*)D
)151      READ(10,*)RHOP
)152      READ(10,*)RH01
)153      READ(10,*)RH02
)154      READ(10,*)S
)155      READ(10,*)XL2
)156      WRITE(11,*)'
)157      WRITE(11,*)' WILKINSON'
)158      WRITE(11,*)'
)159      WRITE(11,*)' INPUT'
)160      WRITE(11,*)'
)161      WRITE(11,*)' PROJECTILE DIAMETER IN CM = ',D
)162      WRITE(11,*)' PROJECTILE DENSITY IN GM/CUBIC CM = ',RHOP
)163      WRITE(11,*)' BUMPER DENSITY IN GM/CUBIC CM = ',RH01
)164      WRITE(11,*)' WALL DENSITY IN GM/CUBIC CM = ',RH02
)165      WRITE(11,*)' BUMPER/WALL SEPARATION IN CM = ',S
)166      WRITE(11,*)' WALL MATERIAL CONSTANT = ',XL2
)167      T1T=0.0
)168      T2T=0.0
)169      DO 56 J=1,64
)170      K=J+8
)171      V=FLOAT(K)

```

```

)172      CALL WILKINSON(V,D,RHOP,RHO1,RHO2,S,XL2,
)173          &           T1,T2,WT,WTCMC)
)174          T1T=T1T+T1*XPV(K)
)175          T2T=T2T+T2*XPV(K)
)176      56    CONTINUE
)177          T1=T1T/3.1335
)178          T2=T2T/3.1335
)179          WT=T1+T2
)180          R12=211.
)181          R22=211.+T2
)182          R11=211.+T2+S
)183          R21=211.+T1+T2+S
)184          VB=4.27*(R21**2.-R11**2.)
)185          VW=4.27*(R22**2.-R12**2.)
)186          WTCMC=RHO1*VB+RHO2*VW
)187          WRITE(11,*)'      OUTPUT'
)188          WRITE(11,*)'
)189          WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
)190          WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
)191          WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
)192          WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
)193          WRITE(11,*)'
)194          WRITE(11,*)'
)195          WRITE(11,*)'
)196          GO TO 10
)197      65    READ(10,*)D
)198          READ(10,*)RHO1
)199          READ(10,*)S
)200          READ(10,*)THETA
)201          READ(10,*)XN
)202          READ(10,*)E1
)203      ***** MODIFIED BURCH *****
)204          WRITE(11,*)'      MODIFIED BURCH'
)205          WRITE(11,*)'
)206          WRITE(11,*)'      INPUT'
)207          WRITE(11,*)'
)208          WRITE(11,*)'      PROJECTILE DIAMETER IN CM = ',D
)209          WRITE(11,*)'      BUMPER DENSITY IN GM/CUBIC CM = ',RHO1
)210          WRITE(11,*)'      BUMPER/WALL SEPARATION IN CM = ',S
)211          WRITE(11,*)'      IMPACT ANGLE FROM NORMAL IN DEGREES = ',THETA
)212          WRITE(11,*)'      NUMBER OF PLATES TO PENETRATE AFTER FIRST',
)213          &          '      BUMPER = ',XN
)214          &          '      BUMPER YOUNGS MODULUS IN GM/CM-SQUARE',
)215          &          '      SEC = ',E1
)216          WRITE(11,*)'
)217          T1T=0.0
)218          T2T=0.0
)219          DO 66 J=1,64
)220          K=J+8
)221          V=FLOAT(K)
)222          CALL BURCH(V,D,RHO1,S,THETA,
)223          &           XN,E1,T1,T2,WT,WTCMC)
)224          T1T=T1T+T1*XPV(K)
)225          T2T=T2T+T2*XPV(K)
)226      66    CONTINUE
)227          T1=T1T/3.1335
)228          T2=T2T/3.1335

```

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```

)229      WT=T1+T2
)230      R12=211.
)231      R22=211.+T2
)232      R11=211.+T2+S
)233      R21=211.+T1+T2+S
)234      VB=4.27*(R21**2.-R11**2.)
)235      VW=4.27*(R22**2.-R12**2.)
)236      WTCMC=RHO1*VB+2.81*VW
)237      WRITE(11,*)'      OUTPUT'
)238      WRITE(11,*)
)239      WRITE(11,*)'      BUMPER THICKNESS = ',T1,'CM'
)240      WRITE(11,*)'      WALL THICKNESS = ',T2,'CM'
)241      WRITE(11,*)'      MIN. WEIGHT = ',WT,'CM'
)242      WRITE(11,*)'      CMC MIN. WEIGHT = ',WTCMC,'KG'
)243      WRITE(11,*)
)244      WRITE(11,*)
)245      WRITE(11,*)
)246      GO TO 10
)247      10    CONTINUE
)248      STOP
)249      END

```

>PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	4826	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	743	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	1028	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	6597	

ENTRY POINTS

Address	Type	Name
0-00000000		IMPACT5VM\$MAIN

/ARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
2-0000019C	R*4	D	2-000001DC	R*4	E1	2-000001A0	R*4	H
2-00000190	I*4	IV	**	I*4	J	**	I*4	K
2-00000194	I*4	NRUNS	**	R*4	R11	**	R*4	R12
**	R*4	R22	2-000001E0	R*4	RHO	2-000001BC	R*4	RHO1
2-000001B8	R*4	RHOP	2-000001C4	R*4	S	2-000001CC	R*4	SY1
2-000001A8	R*4	T1	**	R*4	T1T	2-000001AC	R*4	T2
2-000001D4	R*4	THETA	2-000001A4	R*4	V	**	R*4	VB
2-000001B0	R*4	WT	2-000001B4	R*4	WTCMC	2-000001C8	R*4	XL2

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```
J001      SUBROUTINE NYSMITH(V,D,H,T1,T2,WT,WTCMC)
J002      DMAX=0.24*H**V**-0.2
J003      IF(D.GT.DMAX)THEN
J004          WRITE(11,*)'    NO SOLUTION--PROJ. DIA. TOO LARGE FOR NYSMITH'
J005          GO TO 16
J006      ENDIF
J007      T1=1.93*V**0.18*D**1.91/H**0.91
J008      T2=1.86*T1
J009      16      CONTINUE
J010      RETURN
J011      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	150	PIC CON REL LCL SHR EXE RD NOWRT LONG
1 \$PDATA	49	PIC CON REL LCL SHR NOEXE RD NOWRT LONG
2 \$LOCAL	8	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	207	

ENTRY POINTS

Address	Type	Name
0-00000000		NYSMITH

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	DMAX	AP-0000000C@	R*4	H
AP-00000014@	R*4	T2	AP-00000004@	R*4	V	AP-00000018@	R*4	WT

LABELS

Address	Label
0-00000095	16

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J001 SUBROUTINE BOEING(V,D,RHOP,RHO1,RHO2,S,XL2,SY1,SY2,THETA,
J002 & XN,E1,T1,T2,WT,WTCMC)
J003 ***** PEN4 *****
J004 T1=0.16
J005 V=V*3280.
J006 D=D/30.48
J007 RP=D/2.0
J008 RHOP=RHOP*1.94
J009 RHO1=RHO1*1.94
J010 RHO2=RHO2*1.94
J011 NITSP=0
J012 NITSP=NITSP+1
J013 NP1=0
J014 T1P=T1/30.48
J015 T2P=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P)
J016 WT=T1P+T2P
J017 IF(NITSP.EQ.1)THEN
J018 T1P1=1.1*T1P
J019 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
J020 WT1=T1P1+T2P1
J021 ENDIF
J022 IF(WT1.GT.WT)THEN
J023 T1P1=0.82*T1P1
J024 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
J025 WT1=T1P1+T2P1
J026 590 IF(WT1.GT.WT)THEN
J027 GO TO 601
J028 ELSE
J029 T1P=T1P1
J030 T2P=T2P1
J031 WT=WT1
J032 NP1=NP1+1
J033 IF(NP1.EQ.100)THEN
J034 WRITE(11,*)' NO CONVERGENCE IN PEN4'
J035 GO TO 557
J036 ENDIF
J037 T1P1=0.9*T1P1
J038 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
J039 WT1=T1P1+T2P1
J040 GO TO 590
J041 ENDIF
J042 ELSE
J043 579 T1P=T1P1
J044 T2P=T2P1
J045 WT=WT1
J046 T1P1=1.1*T1P1
J047 T2P1=FT2P(RHOP,V,RP,SY1,THETA,RHO1,SY2,D,RHO2,T1P1)
J048 WT1=T1P1+T2P1
J049 IF(WT1.GT.WT)THEN
J050 GO TO 601
J051 ELSE
J052 NP1=NP1+1
J053 IF(NP1.EQ.100)THEN
J054 WRITE(11,*)' NO CONVERGENCE IN PEN4'
J055 GO TO 557
J056 ENDIF
J057 GO TO 579

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BOEING

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```
)058      ENDOF
)059      ENDOF
)060      601    CONTINUE
)061      D=30.48*D
)062      RHOP=RHOP/1.94
)063      RHO1=RHO1/1.94
)064      RHO2=RHO2/1.94
)065      T1P=30.48*T1P
)066      T2P=30.48*T2P
)067      IF(T1P/D.LE.0.4)VF=4100
)068      IF(T1P/D.GT.0.4)VF=4986*(T1P/D)**0.21
)069      VF=VF+4000.
)070      IF(V.LE.VF)THEN
)071          WRITE(11,*)'    INSIDE OF PEN4 LIMITS'
)072          T1=T1P
)073          T2=T2P
)074          GO TO 1102
)075      ENDOF
)076      557    CONTINUE
)077      ***** WILKINSON *****
)078      V=V/3280.
)079      T1=0.604*D**2.*RHOP/S
)080      T1=T1*SQRT(V/(XL2*RHO1*RHO2))
)081      RATIO=D*RHOP/(T1*RHO1)
)082      IF(RATIO.GT.1.0)T2=T1
)083      IF(RATIO.LE.1.0)T2=T1/RATIO
)084      ***** MODIFIED BURCH *****
)085      VB=V*3280.
)086      DB=D/2.54
)087      CM=SQRT(E1/RHO1)
)088      CM=CM/30.48
)089      SB=S/2.54
)090      IF(THETA.LE.0.001)GO TO 125
)091      CHI=TAN(THETA)-0.5
)092      F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
)093      F2=F2+(1.7-12.*T1B/D)*CHI
)094      F3=0.32*(T1B/D)**0.83
)095      F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
)096      T2F=D*((F1+0.63*F2)/XN)*(CM/V)**2.29
)097      T2F=T2F*(D/S)**0.71
)098      T2N=F3*(CM/V)**1.33*D/XN
)099      IF(T2N.GE.T2F)T2B=T2N
)100      IF(T2N.LT.T2F)T2B=T2F
)101      T2B=T2B*2.54
)102      IF(T2B.GT.T2)NREGION=3
)103      IF(T2B.GT.T2)T2=T2B
)104      GO TO 155
)105      125    CONTINUE
)106      T1B1=T1/2.54
)107      NITSB=0
)108      XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
)109      VDELT=0.0
)110      DELTA3=0.52
)111      1099   DELTA2=2.33*(1.-1.57*DELTA3)
)112      DELTA1=1.33*(2.*DELTA3-1.)
)113      VDELT=1./DELTA1**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
)114      VDELT=VDELT*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
```

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```
J115      IF(VDELT A1.LT.VDELT A)THEN
J116          DELTA1=1.33*(2.*DELTA3-1.04)
J117          T1B=DELTA1*VDELT A
J118          T2B=VDELT A-T1B
J119          GO TO 499
J120
J121      ENDIF
J122      VDELT A=VDELT A1
J123      DELTA3=DELTA3+0.02
J124      IF(DELTA3.GT.0.63)THEN
J125          T1B=DELTA1*VDELT A
J126          T2B=VDELT A-T1B
J127          GO TO 499
J128
J129      ENDIF
J130      GO TO 1099
J131      499  CONTINUE
J132      ***** COMPARISON OF MODIFIED BURCH AND WILKINSON *****
J133      199  CONTINUE
J134      T10W=T1/2.54
J135      F10W=1.58*(DB/T10W)**0.57+2.80*(T10W/DB)**0.57
J136      T2BT10W=(F10W/XN)**1.71*(CM/VB)**2.29*DB**1.71
J137      T2BT10W=T2BT10W/SB**0.71
J138      T2BT10W=T2BT10W*2.54
J139      RATIOB=(DB*RHOP)/(RH01*T1B)
J140      T2WT10B=0.364*D**3.*RHOP*V/(XL2*RH02*S**2.)
J141      IF(RATIOB.GT.1.0)T2WT10B=T2WT10B*RATIOB
J142      IF(T2BT10W.GT.T2)T2=T2BT10W
J143      T2B=T2B*2.54
J144      IF(T2WT10B.GT.T2B)T2B=T2WT10B
J145      T1B=T1B*2.54
J146      IF(T1B+T2B.LT.T1+T2)THEN
J147          T1=T1B
J148          T2=T2B
J149          ENDIF
J150      155  CONTINUE
J151      1102  IF(T2.LE.0.01)THEN
J152          SIGMA=SY2/144.
J153          T2=3099.1/SIGMA
J154          ENDIF
J155      156  RETURN
J156      END
```

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VAX FORTI
SAI_USRDIS

```
)001      FUNCTION FT2B(DB,T1B,XN,CM,VB,SB)
)002      F1=2.42*(DB/T1B)**0.33+4.26*(T1B/DB)**0.33
)003      F1=F1-4.18
)004      FT2B=(F1/XN)**1.71*(CM/VB)**2.29*DB**1.71/SB**0.71
)005      RETURN
)006      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	163	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	167	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2B

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-000000010@	R*4	CM	AP-00000004@	R*4	DB	**	R*4	F1
AP-00000008@	R*4	T1B	AP-000000014@	R*4	VB	AP-0000000C@	R*4	XN

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VAX FORTRAN
SAI_USRDISK

```
J001      FUNCTION FT2P(RHOP,V,RP,SY1,THETA,RH01,SY2,D,RH02,T1P)
J002      A=1.33*RHOP*(V*RP)**2.
J003      B=8.0*SY1*EXP(-3.125E-04*V)/COS(THETA)
J004      C=1.33*RHOP*RP**2.0
J005      D1=RP*RH01/COS(THETA)
J006      XK1=1.67*(RHOP/(2.*SY2))**0.31
J007      XK1=XK1*(0.281*D*RHOP/RH02)**0.33
J008      XK1=XK1*COS(THETA)
J009      C1P1=(A-B*T1P)/(C+D1*T1P)
J010      IF(C1P1.LE.0.001)THEN          ORIGINAL PAGE IS
J011          FT2P=0.0                  OF POOR QUALITY
J012          GO TO 999
J013      ENDIF
J014      FT2P=XK1*C1P1**0.31
J015      999      RETURN
J016      END
```

>PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	222	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 \$LOCAL	4	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	226	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	FT2P

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
**	R*4	A	**	R*4	B	**	R*4	C
AP-00000020@	R*4	D	**	R*4	D1	AP-00000018@	R*4	RH01
AP-00000040@	R*4	RHOP	AP-0000000C@	R*4	RP	AP-00000010@	R*4	SY1
AP-00000028@	R*4	T1P	AP-00000014@	R*4	THETA	AP-00000008@	R*4	V

LABELS

Address	Label
0-000000D9	999

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VAX FORTRAN
SAI_USRD1

```
J001      SUBROUTINE MADDEN(V,D,RHOP,S,RHO,T1,T2,WT,WTCMC)
J002      V=V*1.E05
J003      T1=0.009*SQRT(V)*RHOP*D**2.0
J004      T1=T1/(S*RHO**1.5)
J005      T2=T1
J006      RETURN
J007      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 \$CODE	69	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	69	

ENTRY POINTS

Address	Type	Name
0-00000000		MADDEN

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	AP-00000014@	R*4	RHO	AP-0000000C@	R*4	RHOP
AP-00000018@	R*4	T1	AP-0000001C@	R*4	T2	AP-00000004@	R*4	V
AP-00000024@	R*4	WTCMC						

FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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```
)001      SUBROUTINE WILKINSON(V,D,RHOP,RH01,RH02,S,XL2,  
002          &           T1,T2,WT,WTCMC)  
003          T1=0.604*D**2.*RHOP/S  
004          T1=T1*SQRT(V/(XL2*RH01*RH02))  
005          RATIO=D*RHOP/(T1*RH01)  
006          IF(RATIO.GT.1.0)T2=T1  
007          IF(RATIO.LE.1.0)T2=T1/RATIO  
008          RETURN  
009          END
```

>PROGRAM SECTIONS

Name	Bytes	Attributes
U \$CODE	87	PIC CON REL LCL SHR EXE RD NOWRT LONG
Total Space Allocated	87	

ENTRY POINTS

Address	Type	Name
0-00000000		WILKINSON

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name
AP-00000008@	R*4	D	**	R*4	RATIO	AP-00000010@	R*4	RH01
AP-0000000C@	R*4	RHOP	AP-00000018@	R*4	S	AP-00000020@	R*4	T1
AP-00000004@	R*4	V	AP-00000028@	R*4	WT	AP-0000002C@	R*4	WTCMC

FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name
R*4	MTH\$SQRT

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VAX FORTRAN
SAI_USRD

```
)001      ***** MODIFIED BURCH *****
)002          SUBROUTINE BURCH(V,D,RHO1,S,THETA,
)003          &           XN,E1,T1,T2,WT,WTCMC)
)004          VB=V*3280.
)005          DB=D/2.54
)006          CM=SQRT(E1/RHO1)
)007          CM=CM/30.48
)008          SB=S/2.54
)009          IF(THETA.LE.0.001)GO TO 425
)010          CHI=TAN(THETA)-0.5
)011          F2=0.5-1.87*(T1B/D)+(5.*T1B/D-1.6)*CHI**3.0
)012          F2=F2+(1.7-12.*T1B/D)*CHI
)013          F3=0.32*(T1B/D)**0.83
)014          F3=F3+0.48*(T1B/D)**0.33*(SIN(THETA))**3.0
)015          T2F=0*((F1+0.63*F2)/XN)*(CM/V)**2.29
)016          T2F=T2F*(D/S)**0.71
)017          T2N=F3*(CM/V)**1.33*D/XN
)018          IF(T2N.GE.T2F)T2B=T2N
)019          IF(T2N.LT.T2F)T2B=T2F
)020          T2B=T2B*2.54
)021          IF(T2B.GT.T2)NREGION=3
)022          IF(T2B.GT.T2)T2=T2B
)023          GO TO 499
)024        425    CONTINUE
)025          NITSB=0
)026          XK1=(DB/XN)**1.71*(CM/VB)**2.29/SB**0.71
)027          VDELT A=0.0
)028          DELTA3=0.52
)029        1099   DELTA2=2.33*(1.-1.57*DELTA3)
)030          DELTA1=1.33*(2.*DELTA3-1.)
)031          VDELT A1=(1./DELTA1)**DELTA1*(2.8*XK1/(DELTA2*DB**0.57))**DELTA2
)032          VDELT A1=VDELT A1*(1.58*XK1*DB**0.57/DELTA3)**DELTA3
)033          IF(VDELT A1.LT.VDELT A)THEN
)034              DELTA1=1.33*(2.*DELTA3-1.04)
)035              T1=DELTA1*VDELT A
)036              T2=VDELT A-T1
)037              GO TO 499
)038          ENDIF
)039          VDELT A=VDELT A1
)040          DELTA3=DELTA3+0.02
)041          IF(DELTA3.GT.0.63)THEN
)042              T1=DELTA1*VDELT A
)043              T2=VDELT A-T1
)044              GO TO 499
)045          ENDIF
)046          GO TO 1099
)047        499    CONTINUE
)048          T1=T1*2.54
)049          T2=T2*2.54
)050          RETURN
)051          END
```